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Three dimensional visualization of a coastal mesoscale model

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Three Dimensional Visualization
of a Coastal Mesoscale Model

by

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Abstract

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I. INTRODUCTION

Today, the meteorologist relies on numerical weather model predictions to provide accurate weather forecasts. For the naval meteorologist these forecasts consist not only of predictions for cloud cover, precipitation and other significant weather but include impacts on tactical sensor performance. Numerical weather models cannot directly forecast these variables from current conditions. Instead, numerical models forecast parameters such as vorticity, temperature advection, atmospheric stability and pressure gradients. The forecaster's job becomes interpreting these parameters to prepare the desired forecast of cloud cover, precipitation, significant weather and tactical sensor performance

Interpreting numerical model data is a demanding problem for the forecaster. Models provide complex numerical output of an atmospheric volume. In the past, model output has been either in the form of two-dimensional graphical charts, usually horizontal slices through the model volume, or model output statistics. "Seeing" the model in three dimensions without the need of interpreting from two dimensions would significantly assist the forecaster in deriving the forecast. The purpose of displaying this data in a three-dimensional form is to transform numbers into understanding of weather systems and elements in the forecast.

Today's weapon systems require an understanding of the environment for tactical decision-making. A weapon systems performance can be evaluated by using an atmospheric model; however, the end product is complex and the volume of data

extensive. Visualization can be used to simplify the result in a meaningful representation. The importance of visualization is compounded when critical decisions must be made quickly and skillfully.

In the 1980's, the Navy's development of the Tactical Environmental Support System (TESS) and its follow-on system, TESS3, was a major effort to provide a computer workstation to afloat and forward-deployed units. TESS was designed to receive, process and display large environmental datasets. Along with a direct satellite image capability, the system was designed to receive broadcast numerical model output. In fact, TESS3 software contains the first three-dimensional product: a wire mesh graphic of pressure surface heights. Since the design of TESS there has been a rapid development of high-speed graphical workstations. Currently, there are tremendous opportunities to use the capability of these workstations to visualize numerical model data.

The goal of this thesis is to use a high speed graphical workstation to show model output from a coastal mesoscale model. The paper will focus on two elements. The first element is the display of three-dimensional model output. Scenes will be formed to show the interrelation of model parameters that aid in understanding the model forecast. Second, the thesis will use the model volume data to display tactically significant variables used by the fleet meteorologist.

II. DATA RETRIEVAL

A. MODEL DISCUSSION

The numerical model used for visualization in this thesis was originally developed by the Naval Research Laboratory (NRL). The current NPS/NRL model used in this thesis is a research version of the original model with finer vertical and horizontal resolution. The NPS/NRL model contains more sophisticated planetary boundary layer (PBL), cloud and radiation parameterizations. It is a relocatable three-dimensional, baroclinic, quasi-hydrostatic, primitive equation model based on five prognostic and two diagnostic equations. An explicit description of the model is detailed by Holt and Chang (1993) and Madala et al. (1987).

1. Dimensions and Resolution

The NPS/NRL model grid is centered over the coastal region of the western United States. The horizontal dimensions of the model extend from 28° N to 43° N and 113° W to 130° W. The NPS/NRL model uses a staggered Arakawa C-grid described by Haltiner and Williams (1980). The domain of the model contains 103 by 91 mass grid points with $^1/_6$ degree resolution, approximately 18 km. Topographic relief is represented in the NPS/NRL model. Heights are computed using the U. S. Navy global 10 minute elevation database. The horizontal wind fields are computed between the mass points. At this resolution the capability for the model to resolve mesoscale features is demonstrated in the previous studies of Grandau (1992), Stewart (1992) and Ferandez (1993).

2. Sigma Coordinate System

There are 23 levels based on a vertical terrain-following sigma ($\sigma = \frac{p}{p_{sfc}}$) coordinate system in the NPS/NRL model. To capture important planetary boundary layer (PBL) processes, vertical resolution is increased in the lower one kilometer of the model. For ocean regions in the NPS/NRL model, 13 of the 23 levels are below 850 mb. This allows the model to explicitly resolve vertical PBL structure. Vertical velocities are computed based on this coordinate system. One drawback of a sigma coordinate system is the difficulty in interpolating vertical velocities from a terrain-following surface.

3. Parameterizations

Important aspects of the NPS/NRL model include its parameterizations for clouds, precipitation, radiation and planetary boundary layer (PBL) processes. The cloud parameterization distinguishes between unstable (cumulus) and stable (stratiform) development and their associated precipitation. Convective clouds and precipitation are computed by using a modified Kuo scheme (Kuo, 1974), while a Sundqvist scheme is used for stratiform clouds and stable precipitation (Sundqvist et al., 1989). For convective clouds, three-dimensional fields of cloud fraction are determined from the Kuo convective precipitation rate (Slingo and Ritter, 1985). For stratiform clouds, the critical relative humidity at each mass grid point is utilized (Stewart, 1992).

Atmospheric heating and cooling through radiative processes are parameterized in the model using the scheme developed by Harshvardhan et al. (1987). Longwave cooling is computed by approximating the emmisivity and absorption of water vapor, ozone and carbon dioxide. Shortwave heating is calculated by estimating the

transmission of solar radiation. The amount of shortwave transmission is modified by Rayleigh scattering and cloud reflection and is a function of optical depth. A further description of the radiation parameterization in the NPS/NRL model may be found in Stewart (1992).

Parameterizations for the planetary boundary layer include a turbulent kinetic energy (TKE) closure scheme (Holt et al., 1990), a convective soil temperature slab model (Blackadar, 1976), and surface layer Monin-Obokov similarity theory (Businger et al., 1971).

4. Model Run

The archived Fleet Numerical Oceanographic Center's (FNOC) Navy Operational Global Atmospheric Prediction System (NOGAPS) 2.5 degree global analyses are used for initialization of the NPS/NRL model. Fields used were sea level pressure, sea surface temperature, D-values, u and v wind components, temperature and specific humidity. D-values were converted to geopotential heights using NACA standard atmosphere conditions (Haltiner and Martin, 1972). NOGAPS has 16 vertical pressure levels ranging from the surface to 10 mb. Vertical interpolation from 16 NOGAPS levels to 23 sigma levels was linear in log pressure for temperature, exponential in pressure for specific humidity, and linear in pressure for u and v. Horizontal interpolation was by cubic polynomial. Nondivergent initialization on sigma surfaces was used. The initial and lateral boundaries conditions are interpolated to hourly from the 12-h NOGAPS analyses. The relaxation method of Davies (1976) is used for the boundary treatment over the

outermost five grid points (Chang et al., 1989). The forecast period starts at 0000 UTC 02 May 90 and is integrated to 36 hours, 1200 UTC 03 May 90. The model was run on the Naval Postgraduate School Cray Y-MP EL 98 and output every 30 minutes to provide a near continuous animation.

B. MODEL OUTPUT

Output from the model is saved to disk in unformatted binary files. These files contain 32 variables saved at 30 minute time increments. A Fortran program, EXTRACT.f, is written to extract each variable's data to separate scaled-byte files. The important variables, with their descriptions and units, are given in Table 1.

Output files from EXTRACT.f are scale-byte format that contains eight-bit or one byte words. Data for all grid points at each level and time step are scaled to this one byte word. Each level contains three header lines having all the necessary information: latitude, longitude, height, scaling factor to unpack the data to floating point numbers (losing the appropriate resolution).

1. Data Conversion

a. Vertical Coordinates

One of the primary tasks of the extraction program is to convert the sigma coordinates of the model to pressure coordinates. The subroutine "Sigma2P" modifies each three-dimensional variable before writing the output files. This subroutine computes the pressure at each sigma level and compares this pressure to the requested pressure

surfaces The data is then interpolated to the desired pressure level using the surrounding sigma levels.

b. *Density Field*

Using the model output data files, a three-dimensional density field is computed in the extraction program. This field is used to calculate the radar trapping layers and the radar propagation losses described in the tactical analysis of this thesis. Density (ρ) is computed using the equation of state and the values for sigma, surface pressure and temperature

$$\rho = \frac{p}{RT} \qquad \text{where } p = \sigma P_{sfc}$$

c. *Heights Field*

Also used to compute the radar parameters, pressure surface heights are computed by adding the topography field (multiplied by gravity) to the geopotential field. The sum is then divided by gravity and converted to meters.

Table 1

NPS/NRL Model Output Variables

Variable Name	Description	Units
	Three-dimensional Fields	
U2	U Velocity Field	cm/sec
V2	V Velocity Field	cm/sec
T2	Temperature Field	Kelvin
Q2	Specific Humidity Field	grams/gram
P1	Geopotential Height Field	cm^2/sec^2
DUMMY	Omega Field	microbars/sec
QM1	Cloud Liquid Water Field	grams/kilogram
RSW	Shortwave Radiation	deg C/sec
RLW	Longwave Radiation	deg C/sec
STRATUS	Stratus Cloud Fraction	Ratio (0 to 1)
CFR	Total Cloud Fraction	Ratio (0 to 1)
	Two-dimensional Fields	
PS2	Surface Pressure	$dynes/cm^2$
USTAR	Friction Velocity at Reference Level	cm/sec
TSTAR	Convective Temperature Scale at Reference Level	Kelvin
QSTAR	Specific Humidity at Reference Level	grams/gram
PRCPC	Convective Precipitation	cm
PRCPN	Nonconvective Precipitation	cm
RPRCPC	Rate of Convective Precipitation	cm/sec
RPRCPN	Rate of Nonconvective Precipitation	cm/sec
TG	Surface Temperature	Kelvin
TM	Deep Soil Temperature	Kelvin
TOPO	Topography	meters

d. Wind Fields

Wind fields require special processing in the extraction program. Both U2 and V2 wind fields are staggered on the Arakawa C-grid. The U2 field contains one less grid point along the longitude axis than the other three-dimensional fields and the V2 field contains one less grid point along the latitude axis. Data is linearly interpolated between each grid point in the appropriate direction and the end grid points are extrapolated to increase the dimensions of the U2 and V2 field consistent with the other 3D fields. Computation of vertical motion requires the conversion of microbars/sec(ω) to cm/sec. The subroutine "convertW" transforms vertical motions by the formula.

$$w = -\omega/\rho g$$

e. Two-dimensional Fields

The two-dimensional fields listed in Table 1 are transformed to three-dimensional volumes before output. This is required to visualize two-dimensional fields alongside the three-dimensional fields

2. Scale-byte To VIS-5D File Format

VIS-5D, the visualization software used in this thesis, was originally developed to be used with the University of Wisconsin Man-computer Interactive Data Access System (McIDAS). A complete description of VIS-5D is contained in the following chapter. Implementing VIS-5D to display the NPS/NRL model output requires several conversions of the original data to the proper VIS-5D format. These conversions are invoked by the program "op2grid." This program is authored and maintained by the Naval Postgraduate School Visualization Lab to facilitate the conversion of scaled-byte data files

to VIS-5D data format. Two points need to be made concerning op2grid. First, the program was originally designed for oceanographic applications. Therefore, the program references ocean depths as positive values. To look at the atmosphere, the meteorologist must pass in negative values of height - this is done within EXTRACT.f. Second, op2grid assumes that the horizontal and vertical wind velocities are in centimeters/second (another oceanographic standard). It then proceeds to convert these velocities to m/s required by VIS-5D to compute accurate trajectories.

III. VISUALIZATION

A. VIS-5D

1. Description

The software package utilized for this thesis is VIS-5D, version 3.2 (Hibbert and Santek, 1991). The package is a public domain package that was developed at the University of Wisconsin Space Science and Engineering Center as part of their larger Man-computer Interactive Data Access System (McIDAS). Originally developed in 1988 to visualize large numerical datasets on a Stellar GS-1000 computer, VIS-5D has recently been revised to run on a variety of workstations. The term "5D" is derived from the fact that the program visualizes data in three spatial, one temporal, and one multivariable dimension. Therefore, VIS-5D allows for the animation of three-dimensional datasets of several different variables.

VIS-5D uses two windows to visualize data. The first window is the control window (Figure 1). The control window is a graphical pushbutton window that controls the rendering of the displayed images. From this window two-dimensional contour slices and three-dimensional isosurfaces may be generated. Topography and a map outline may be selected and displayed. With the exception of a few keystrokes to select specific values, all user input is by the mouse. A "perspective" button is available to change the orthogonal viewing projection to a perspective projection. A perspective projection provides visual depth to the rendering of the volume. In an orthognal view, the projected size of the volume is independent of the viewing distance. Additional controls are

available including the "save pic" button that is used to save all the VIS-5D figures shown in this thesis to a graphics image file (.GIF).

The second window is the display window. This window displays model data in the three-dimensional space. The view of the volume in this window may be rotated, zoomed or translated. The data is "seen" by rendering isosurfaces, contour and shade slices, and wind vectors of the variables selected.

In order for VIS-5D to rapidly display this information to the graphics window, all data must first be loaded into memory. This precondition makes VIS-5D a memory intensive program. VIS-5D manages this memory requirement by scaling the data. All data inputted to VIS-5D is scaled to one byte or eight-bit words. In binary, eight-bit words may contain 256 (2^8) possible values. Floating point numbers, that are normally stored as 32 or 64 bits, are compacted and scaled to fit this smaller word size. To accomplish this scaling each variable is scanned for minimum and maximum values. An increment is computed which will cover the entire range of values with 255 possible numbers (one value is retained to signify "no data").

2. Features

a. Contouring (slices)

Two-dimensional planar cross sections may be visualized in VIS-5D. Data in the cross sections may either be depicted by contour lines, color shading or, if horizontal and vertical velocities are available, wind vectors. These two-dimensional slices may be taken vertically or horizontally through the volume and may be moved by "dragging" the corner of the slice with the mouse.

b. Isosurfaces

Three-dimensional contour surfaces may be created with VIS-5D. The surface shows the data bounded by a particular isovalue. Data inside the surface contains values either greater or less than the isovalue. Generating the isosurfaces requires a moderate amount of numerical computations. VIS-5D speeds this process by utilizing all available computer processors on a multiprocessor machine.

c. Volume Rendering

A new feature of the 3.2 version of VIS-5D is volume rendering. It requires specialized graphical hardware which in found on upper-end workstations. Each grid point in the volume is assigned a "fog" intensity and color based on the data value. Unlike an isosurface where the visualized surface is based on a critical data value, the volume fog provides a continuous representation through color intensity of all data values.

d. Trajectories

For datasets that contain horizontal and vertical velocities (U, V, W wind component variables) at multiple time steps, VIS-5D can display trajectories of air parcels. Analogous to smoke trails in a wind tunnel, trajectories trace the motion of air through the three-dimensional volume. Control of the trajectories is through an interactive window where the position, length and starting time step is governed.

e. Probe

Specific values may be determined by using the probe function in VIS-5D. A cursor appears in the display window when using this function. Using the mouse, the cursor may be moved within the volume. The data values at the cursor position are shown

in the lower left corner of the display window. Values are interpolated between grid points.

f. External Functions

A powerful feature of VIS-5D is the external function. VIS-5D spawns a user Fortran program that, upon completion, passes a new "computed" variable back to VIS-5D for display. The user function is executed once for each time step. A four dimensional array of each time step's data is passed to the user function that is available to compute the new variable. Upon successful completion of the external function, an additional row is added to the variable list and may be displayed like any other variable.

B. VISUALIZATION TECHNIQUE

Creating viable scenes with VIS-5D requires coordinating model output with computer resources. The NPS/NRL model output consists of 32 three and two-dimensional fields listed in Table 1. Using the spatial dimensions of the model, 91 x 103 x 23 (the 23 pressure levels are specified in Table 2), 72 time steps of 32 variables, requires a total memory of 497 megabytes (MB). The computer used for the visualization, a Silicon Graphics 380 VGX workstation with 8 independent processors, contains 256 MB of memory. Thus, the "design" of the visualization is tailored to fit this machine. After exploring each variable independently, the final visualization is divided as three separate runs: the cloud scene, the model parameter scene, and the radiation scene. Each scene contained the necessary variables to explore different aspects of the model and are summarized in Table 3. The final scale-byte file sizes of the cloud, model and radiation

scenes are limited to 50-70 MB. Performance by the workstation is maintained using this file size as the upper limit.

C. Limitations

Several difficulties exist in visualization of model output. Some of these problems are surmountable by changing procedures or software code; some problems remain and must be acknowledged as such.

1. Vertical Stretching

The height values displayed on the sides of the VIS-5D volume box are computed differently than the model heights. The VIS-5D heights are assumed to vary linearly from the bottom to top. Heights within the model domain are computed correctly from the model variables to each interpolated pressure surface. These pressure surfaces, listed in Table 2, are positioned in the VIS-5D volume rendering equidistant from each other. Figure 2 shows the difference between the contoured model heights and the VIS-5D labels in the cloud scene. In the real atmosphere, height

Table 2

Pressure Surfaces Visualized by VIS-5D

Pressure Surface	Average Height from MSL	Variation of Height in Pressure Surface
1016 mb	33 meters	85 meters
1008 mb	69 meters	151 meters
1000 mb	134 meters	171 meters
992 mb	200 meters	172 meters
984 mb	268 meters	172 meters
976 mb	335 meters	175 meters
968 mb	404 meters	173 meters
960 mb	473 meters	172 meters
952 mb	543 meters	170 meters
936 mb	685 meters	168 meters
920 mb	830 meters	165 meters
900 mb	1013 meters	164 meters
875 mb	1248 meters	163 meters
850 mb	1489 meters	162 meters
825 mb	1735 meters	160 meters
800 mb	1989 meters	161 meters
775 mb	2249 meters	161 meters
750 mb	2515 meters	163 meters
700 mb	3073 meters	176 meters
600 mb	4295 meters	273 meters
500 mb *	5696 meters	395 meters
400 mb *	7343 meters	590 meters
200 mb *	12032 meters	894 meters

* Cloud Scene Only

Table 3

VIS-5D Scenes

Cloud Scene	Model Parameter Scene	Radiation Scene
30 Minute Time Steps	One Hour Time Steps	One Hour Time Steps
Stratus Cloud Fraction	Stratus Cloud Fraction	Stratus Cloud Fraction
Convective Cloud Fraction	Convective Cloud Fraction	Convective Cloud Fraction
Stratus Precipitation Rate	Surface Pressure	Shortwave Radiation
Convective Precipitation Rate	Temperature	Longwave Radiation
Heights	Specific Humidity	Temperature
	Heights	Surface Temperature
	Density	
	U velocity	
	V Velocity	
	W Velocity	
	Total Wind Speed	

varies vertically as the log of pressure. It is important to realize that the rendering of the volume is stretched at the lower levels.

2. Scaled-byte Resolution

To conserve memory, variable data in VIS-5D is scaled into one byte words. For visualization this does not pose any difficulty. However, when using the external function feature of VIS-5D, the loss of resolution may present problems with numerical calculations. Variables with a wide range of values will lose accuracy when utilized as one eight-bit word. In this thesis the problem is apparent when computing dM/dz (see chapter IV for an explanation of dM/dz). In this example, a height field varying from 0 to 5000 meters (500 mb) has less than 20 meters resolution when stored as a one byte word Computing vertical gradients from layers separated by small distances will cause excessive gradient values (or zero divide errors). VIS-5D is capable of reading and passing full resolution data from an uncompressed McIDAS-formatted file. However, for this thesis only the scaled data are utilized. To overcome this problem two conditions are imposed on the data selection. First, only the lower half of the vertical structure of the model is visualized. When investigating dM/dz, the top layer of the volume is restricted to 500 mb (approximately 5000 meters). Second, the pressure surfaces in the visualization are chosen so the height spacing between layers is greater than 50 meters.

3. Topography

The topography of the NPS/NRL model is different from the topography displayed by VIS-5D. The vertical stretching discussed earlier is responsible for this conflict in topography. The conflict is readily apparent in scenes where two-dimensional cross sections cut across the topography. Large areas above the topography did not contain data values. A minor software change is invoked in VIS-5D to help reduce the mismatch. This mismatch of topography to data can be seen in Figure 2 as a black no-data area over the VIS-5D topography

4. Passing Arguments to External Functions

The radar propagation external function (discussed in chapter IV) requires VIS-5D's probe cursor position as the location of the radar. Purely a design decision, VIS-5D software code is modified to pass these needed values.

IV. RESULTS

The principal goal of this thesis is to display realistic scenes of clouds and precipitation as forecast by the NPS/NRL model. The cloud scene shows the model's "end result" using the fundamental equations and integrated parameterizations. Following the cloud visualization, the next logical step is to investigate the development of these clouds within the model. Stratus development near the central California coast is explored as a function of low level moisture and temperature. Wind direction also plays an important role in this stratus development. The impact of the radiation parameterization is also probed to study it's impact on the persistence of the stratus clouds through the following day. The dynamics seen in the model shows a strong interaction of the coastal topography, the synoptic flow and the northern edge of the stratus.

A second goal of this thesis is to apply the visualization technique to a naval application, namely radar propagation. Radar trapping layers and radar propagation loss are computed using the VIS-5D external function feature utilizing the NPS/NRL model as input. The results are displayed using the visualization features of VIS-5D.

A variety of scenes are recorded to video tape that is available upon request (Appendix A). Specific images discussed in this chapter are captured as image files. These images are grouped together as a color section in Appendix B.

A. MODEL VISUALIZATION

1. Cloud Scene

The first scene recorded on the video tape is the stratus and convective clouds in the model. The animation begins at 0030 UTC 02 May 90 and increments through 72 time steps each half hour.

As described in Corkill (1991) the passage of a shortwave through California before the initial period cleared the low-level stratus from the California coastal region. Using the volume rendering feature of VIS-5D, the values for stratus cloud fraction appear as a realistic-looking white stratus deck seen in Figure 3. The whitest intensity corresponds to the largest values for stratus cloud fraction. The only stratus present at the initial time step is in the southwest corner of the model region. Animating through 72 time steps the stratus moves east to the northern coast of Baha, Mexico and progresses up the coast to southern California (Figure 4). Additionally, stratus develops off the central California coast during the night hours. By the following day the northern edge of the stratus is off San Francisco, California and extends well offshore (Figure 5). During the daytime hours the stratus retreats from the coast and the northern edge of the stratus moves south (Figure 6). Two visible satellite images, figures 7 and 8 correspond to figures 5 and 6 of the model output. The model generally shows good agreement with the stratus seen in the satellite images. The exception is the southerly surge event off the central California coast from Morro Bay to Monterey Bay. The model's failure to forecast this mesoscale feature is discussed by Grandau (1992).

Convective clouds develop in the model over the mountains in California. A value of 0.7 is used for generating the visualized isosurface. The initial convective development is seen at 1700Z (1000 local) with the peak convective activity shown in Figure 9 at 2300Z (1600 local). The convective activity decays in the early evening and is not evident by 0300Z (2000 local). Precipitation is developed in the model associated with this convective activity. A translucent gray isosurface using a isosurface value of 0.0001 cm/s is seen as precipitation rate in the visualization.

2. Stratus Formation

This section investigates the model's development of stratus off the central California coast. The formation of stratus in the model is based on a critical relative humidity. Figure 10 shows both specific humidity and temperature at a height of 50 meters in the early evening (0400 local). Animating through the sequence, the low level temperature near Monterey Bay drops below 285 K or 12 °C. In this region the model forms stratus where there is at least 8 g/kg specific humidity and the temperature drops to 285 K.

To understand the decrease in lower level temperature that caused the model's development of stratus, one must study the model's low level wind fields. Figure 11 displays purple wind vectors at 50 m height and the light blue wind vectors at 250 m for 0700Z (midnight). Particle trajectories are shown as larger arrows. As the model advances through time, the 50 m winds become oriented parallel to the coast thus supplying the necessary moisture for stratus development. The 250 meter wind is initially

northwesterly but turns offshore as a classic night land breeze. This cold outflow moves through the gaps in the central coast topography and mixes with the moist marine layer. The air saturation exceeds the model's necessary critical relative humidity and stratus forms.

3. Radiation Parameterization

Once formed, two factors affect the growth or dissipation of the stratus. The first factor is the cool sea surface temperatures. Along the central California coast the sea surface temperature is held at near 285 K, approximately the same temperature as the overlying stratus deck. Thus, there is minimal heat transfer from the sea surface to the cloud deck. The second factor is the radiation parameterization in the model. The longwave cooling in the free atmosphere from the cloud deck is significant. Loss of heat in the stratus deck due to longwave cooling (seen as a cross-section display in Figure 12) averages 40 degrees per day over a narrow region near the cloud top. The following day shortwave radiation is developed by the model's radiation parameterization. In the stratus deck the values of shortwave radiative warming are significantly lower (Figure 13), only 2-3 degrees per day, while the longwave cooling remains considerably higher. Therefore, once the stratus forms in the model, it persists until some other advective process modifies the stratus.

4. Factors Controlling the Northern Boundary of Stratus

This section investigates the factors controlling the northern boundary of the stratus deck in the model. As stated before, stratus clouds in the model are based on a

critical relative humidity. Changes to specific humidity and temperature will be reflected in the northern stratus boundary.

a. Upper Level Synoptic Flow

Important to the stratus boundary is the upper level synoptic flow. At 500 mb the flow is mostly southward shown by the yellow trajectories in Figure 14. The light blue trajectories are at 800 mb or approximately 2500 meters. Over Central California the 800 mb flow is from the northeast and directed offshore.

b. Topographically Enhanced Subsidence

The 800 mb flow creates topographically enhanced subsidence along the lee slopes of the coastal mountain range of northern California. The purple surfaces seen in Figure 15 denote downward motion greater than 30 cm/s. Trajectories of these air parcels are shown in red. Their initial altitude is 2500 meters but, due to the topographically enhanced subsidence, descend quickly to a height to 500 m. The adiabatic warming associated with this downward motion is readily illustrated by the 292 K isosurface of temperature that extends downstream from the purple generation regions.

At 2300 local time, the pulse of warm air extends further offshore and is coincident with the northern edge of the stratus. The pulse separates from shore in the early morning hours. At approximately 0800 local the following morning, a new pulse of warm air is generated along the lee of the coastal mountains of California. Additionally, flow down the west slope of the Sierra Nevada's generates a 292 K isosurface. Throughout the animation the stratus deck remains coincident with the leading edge of this 292 K isosurface (Figure 16).

The diurnal pulses of warm air clearly influence the stratus in the NPS/NRL model. The southwest to northeast diagonal slice in Figure 16 is the cross-section orientation for figures 17 through 19. The cross sectional view is from the northwest looking southeast. To the left is the Northern California coastal mountains. The temperature contours in Figure 17 show a large inversion above a shallow marine layer. The axis of the temperature pulse is at 500 m and signifies the top of the inversion. Potential temperature is contoured as a cross-section in Figure 18. The vertical gradient of potential temperature indicates the stability of the layer. The top of the marine layer slopes upward from approximately 100 m off San Francisco to 300 m further offshore. A strong separation between the marine layer and the upper level flow is exemplified by the number of closely spaced potential temperature contours.

Animating the cross sectional view shows the progression of the temperature pulse offshore. Starting in the evening the daytime heating ends and the temperature pulse becomes thinner. The top of the marine layer initially lifts from 50 m to 150 m near the coast.

5. Coastal Jet

During the late afternoon period starting at 1800 local, a low level jet forms off the Northern California coast. This mesoscale phenomena is visualized in Figure 16 and Figure 19 with a light green 25 m/s isotach that can be seen under the translucent temperature isosurface.

This coastal jet was studied extensively during the Coastal Ocean Dynamics Experiment (CODE) in the early 1980's and is described as an example of supercritical channel flow by Winant et al. (1988). They attributed this mesoscale feature to the interaction between the coastal mountains, the low level inversion and spatial structure of the surface wind.

In the model's domain, the low level jet hugs the base of the inversion and is associated with a region of strongly sloping potential temperature contours. This model simulation of the coastal jet parallels Winant's findings.

B. TACTICAL VISUALIZATION

1. Radar Trapping Layers

Of significant interest to naval operations is radar propagation. Environmental factors can play a major role in a radar's performance. Vertical gradients of a modified refractive index, dM/dz, where M is a measure of refractivity, are computed in a VIS-5D external function. M is derived from VIS-5D fields of temperature, specific humidity, height and atmospheric density. A function of temperature and specific humidity, negative dM/dz signifies radar trapping layers in the atmosphere. M is defined as:

$$M = N + (157km^{-1})z$$

Refractivity, N, is expressed as:

$$N = \left[77.6\frac{K}{mb}\right]\frac{P}{T} - \left[5.6\frac{K}{mb}\right]\frac{e}{T} + \left[3.73E05\frac{K^2}{mb}\right]\frac{e}{T^2}$$

In these layers radar energy is refracted downward and the energy is caught in a duct. Inside the duct extended radar ranges are possible.

In Figures 20 and 21 negative dM/dz values for morning (1500Z) and an afternoon (0000Z) are shown as light blue isosurfaces. In the latter case strong trapping layers form off the central California coast during the late afternoon These trapping layers are generated as a result of the diurnal pulses of warm temperature created by the topographically enhanced subsidence in the region. In Figure 22 the radar trapping layer slopes from a height of 300 m in the south to a height of 100 m further north.

2. RPO

a. Description

Radio Physical Optics (RPO) is an energy loss model that integrates ray optics with parabolic equation (PE) methods to model tropospheric radar propagation. RPO's input are range dependent profiles of modified refractivity (M).

Parabolic equation methods given by Tappert (1977) provide skillful radar propagation forecasts but suffer the disadvantage of being computationally intensive. This disadvantage is compounded when computing propagation loss at higher frequencies, larger antenna beamwidths, and high altitudes. To overcome this disadvantage RPO uses different numerical methods in four separate regions, the flat earth (FE), ray optic (RO), PE and extended optical (XO) regions (Hitney, 1992).

A FE ray optic model ignores refractive and earth-curvature effects. For propagation loss predictions RPO uses the FE model when within 2.5 kilometers of the transmitter. The second method is a full ray optic model that considers refractive and earth-curvature effects. The RO is utilized for ranges beyond the FE and for regions that are above a critical grazing angle of reflected energy from the transmitter. The PE model

is run for regions not covered by the FE and RO models. The PE region is also limited by a critical height. Above this height the XO method uses the upper boundary of the PE model to greater heights. A more detailed discussion of the four methods employed by RPO is documented in Hitney (1992). Keeping the critical grazing angle small limits the computations needed by the PE model, significantly decreasing the necessary numerical calculations. Hitney (1992) validated RPO against a straight PE method and found no significant differences in their results but saw a large decrease in the computer run time for the RPO model.

b. Implementation

RPO is implemented in this thesis using the external function feature of VIS-5D. The data contained within VIS-5D are used to derive the necessary input needed by RPO and the output from RPO is returned to VIS-5D for visualization. The design of the VIS-5D/RPO visualization can be described in four fundamental steps.

(1) Initialization. The location of the radar is chosen by using VIS-5D's probe feature. This required a minor software change within VIS-5D. The cursor is placed to the desired latitude, longitude and height before invoking the RPO external function. This position is transmitted to the external function along with the volume data normally passed by VIS-5D. Within the external function the closest grid point to the cursor is chosen for the radar transmitter. Standard radar characteristics like frequency and antenna type are "hard-coded" into the external function.

(2) Extracting Grid Point Data. For each time step, RPO is run on sixteen different radial azuimths. The first azimuth is due north, the second north-northeast, the third northeast and so on. Each azimuth crosses additional grid points along it's 500 km length. At each grid point the required data is extracted to build the RPO environmental input fields.

(3) Computing Refractivity Profiles. RPO requires height and M-unit arrays for each grid point. The height array is directly available from VIS-5D. The M-unit array is derived from the same equation as described earlier for dM/dz. As stated before, pressure levels must be adequately spaced (50 m or greater) to avoid scale-byte resolution problems with the height field passed to RPO.

(4) Interpolating to Grid Points. The final step in the RPO external function is to interpolate values to grid points that fall between the RPO azmuiths. For each empty grid point the surrounding RPO azimuths are sampled. A weighting scheme computes a result based on range and angle. The result is a cylindrical volume that is passed back to VIS-5D.

c. Limitations

RPO does not model irregular land topography. It is designed to be used over an ocean environment.

d. Visualization

RPO is run using the model parameter scene data. The transmitter location is chosen to be 32° 45' North latitude, 124° 00' West longitude and is positioned at a height of 75 meters. Due to its computationally intensive nature, RPO is only run for 4

time steps, 0800, 1100, 1400 and 1700 local. Each time step took approximately 15 minutes of CPU time to execute on the Silicon Graphics workstation (the external function feature only utilizes one processor).

Figures 23 and 24 show the RPO propagation loss associated with the NPS/NRL model's output at 0800 and 1700 local. At a height of 300 m, high energy loss is shown in red on the horizontal cross-section. The lack of red to the north at 1700 signifies extended radar ranges. This correlates with the strong temperature inversion and trapping layers discussed previously. The greatest ranges are seen as the horizontal cross-section moves vertically through the trapping layers. Above the trapping layer ranges become mostly symmetrical.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study has demonstrated that three-dimensional visualization is a powerful tool in improving the forecaster's understanding of atmospheric dynamics and model processes. Graphical representation of the model output fields provides a direct understanding of the significant elements of the forecast.

The NPS/NRL model utilized in this work contained key elements that enhanced the visualization. First, the model's 18 km resolution resolves mesoscale features. In addition, the model contains topography consistent with the 18 km resolution. Another key element of the model is the parameterizations for clouds, radiation and boundary layer. These features prove significant in accurately depicting the complex coastal environment of California.

Three-dimensional scenes are created and viewed. The first scene is a realistic cloud visualization of stratus and convective activity. Subsequently, the development and movement of stratus in the model is investigated. The initial development of stratus off the central California coast is tied to the mixing of moist marine air with the cold low level land breeze at night. Longwave and shortwave radiation parameterizations within the model explain the persistence of the stratus through the following day. The northern boundary to the stratus is related to the topographically enhanced subsidence seen in the

lee of the Northern California coastal mountains. A coastal low level jet is visualized along the Northern California coast.

Finally, the NPS/NRL model forecast is linked to a radar propagation loss model providing a tactical prediction of a radar's performance. A diurnal cycle associated with the coastal dynamics of central California is observed in the visualization. RPO results correlated with expected theoretical radar propagation responses to the model's atmospheric structure.

B. RECOMMENDATIONS

The use of VIS-5D to view the NPS/NRL model provides an enhanced level of understanding of the model's forecast. In fact, the visualization furnishes many additional questions for further study. Recommendations for future work include the development of a streamlined data conversion system, additional features to VIS-5D, and new validations of additional features seen in the NPS/NRL model.

The naval meteorologist needs a three-dimensional visualization capability. VIS-5D is a versatile, well written software package that contains most of the appropriate features. For the Navy, further revision would be desired. The conversion of the NPS/NRL model output to the VIS-5D format is not straightforward. The process converted the original data to a scale-byte format, returns the data to expanded form, and then rescales the data into another scale-byte format. This lengthy process could be streamlined by expanding VIS-5D's data import capability. An interactive file selection window to allocate (ingest) or deallocate (unload) each variable independently from

memory would be a preferred design. A second issue is the inability of VIS-5D to accurately render topography in a nonlinear vertical axis. Another useful tool for VIS-5D would be a "sounding" feature. Similar to the probe function, the sounding would display a variable's data in a vertical graph. Finally, the warping of military maps or satellite imagery over the topography instead of color-fill would create a more useful tactical display.

The NPS/NRL model develops a low level jet off the Northern California coast. This mesoscale feature has not been studied in the previous works of Corkill (1991) and Grandau (1992). Further study of the model's development of this jet in addition to validation with observations is warranted.

The linking of the NPS/NRL model with RPO has not been completely studied. The promising results generated by this thesis need additional scrutiny. The parameterized PBL is an important feature in the NPS/NRL model and should develop reliable refractivity profiles. However, the M profiles derived from the NPS/NRL model must be validated against observations (soundings).

APPENDIX A

Video Tape of NPS/NRL Model Visualization

The scenes discussed in the model and tactical visualization chapters of this thesis are recorded to video tape (VHS format). The tape is 10 minutes in length and includes animation of the cloud scene developed by the parameterizations in the NPS/NRL model There is an "investigative" portion of the video that explores the model's development and movement of the coastal marine stratus

If interested in obtaining a copy of this video tape contact:

Prof. C. Wash
Code MR/Wx

at:
Naval Postgraduate School
Monterey, CA 93943-5000

Network access on OMNET:
C.WASH

Or on INTERNET:
Wash@lady.met.nps.navy.mil

APPENDIX B

Color Slide Section - Figures 1 through 24

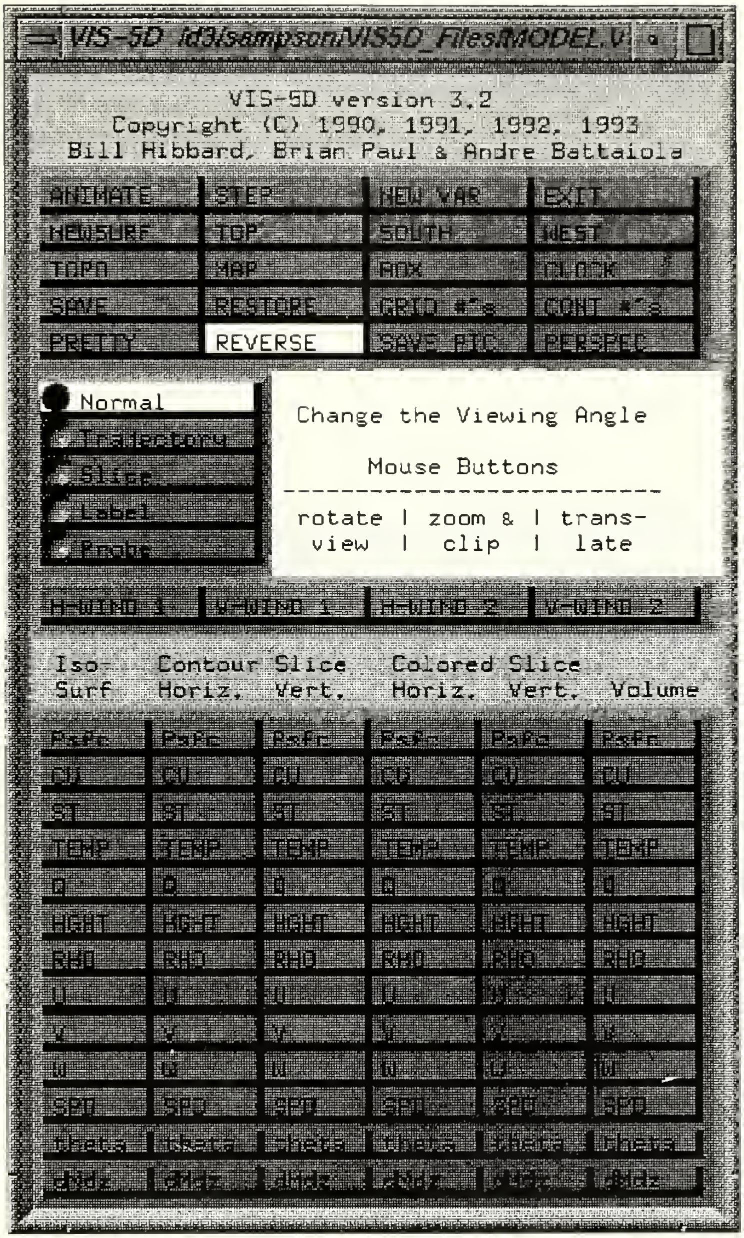

Figure 1.VIS-5D Control Window for the Model Parameter Scene

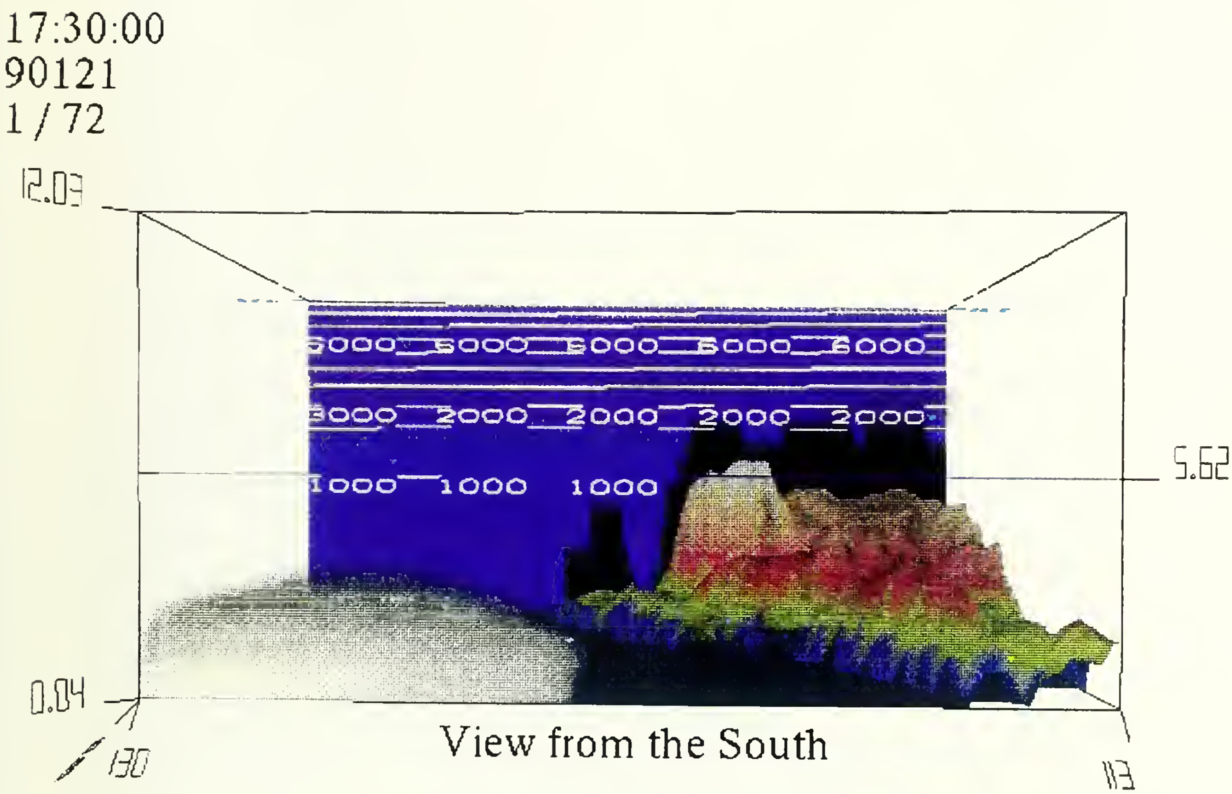

Figure 2. Example of Vertical Stretching. Top layer is 200 millibars or approximately 12,000 meters. Model Heights are shown in meters and VIS-5D Heights (box labels) are shown in kilometers. Time in upper right corner is local.

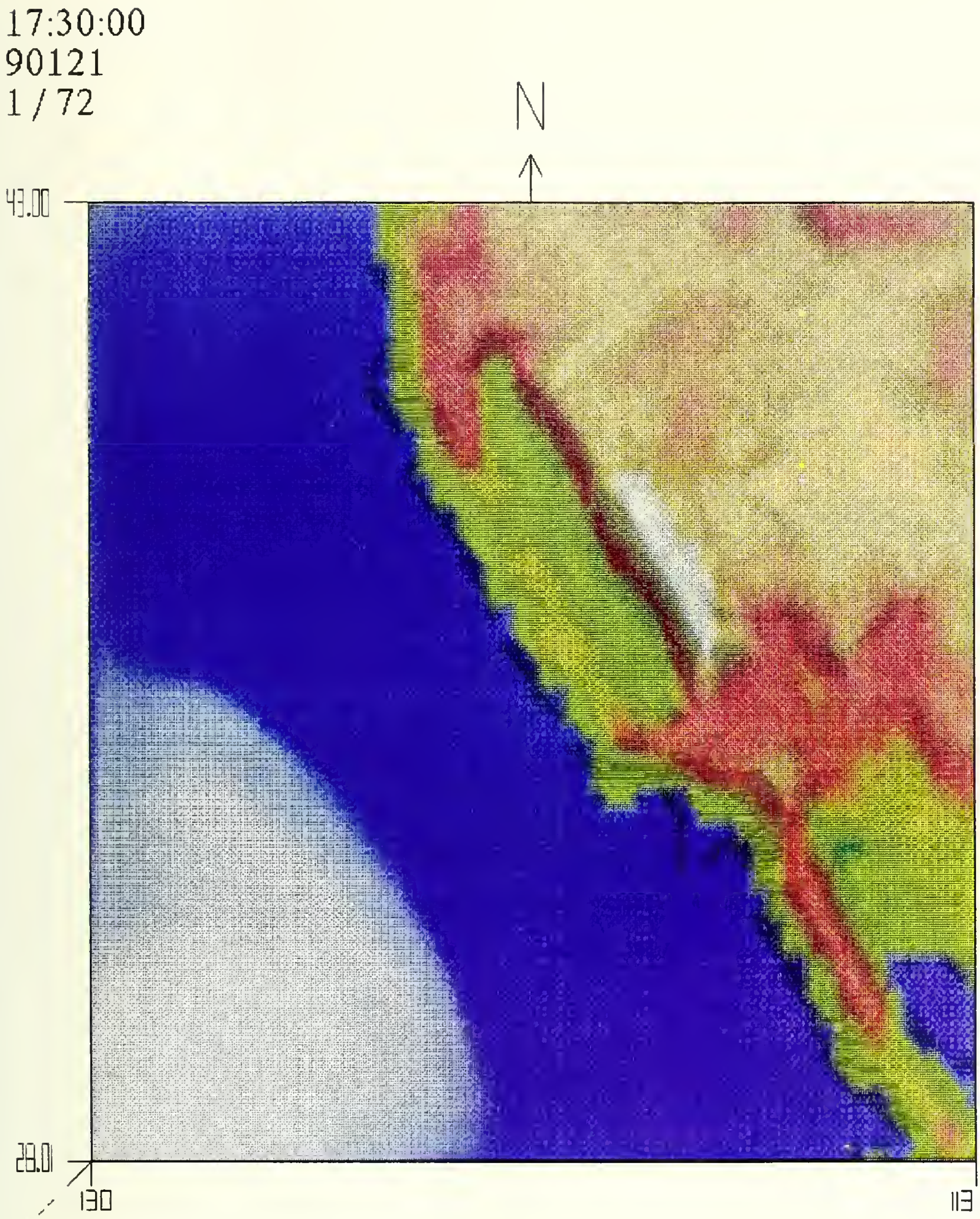

Figure 3. Model Stratus Cloud Fraction, 0030 UTC 02 May 90.

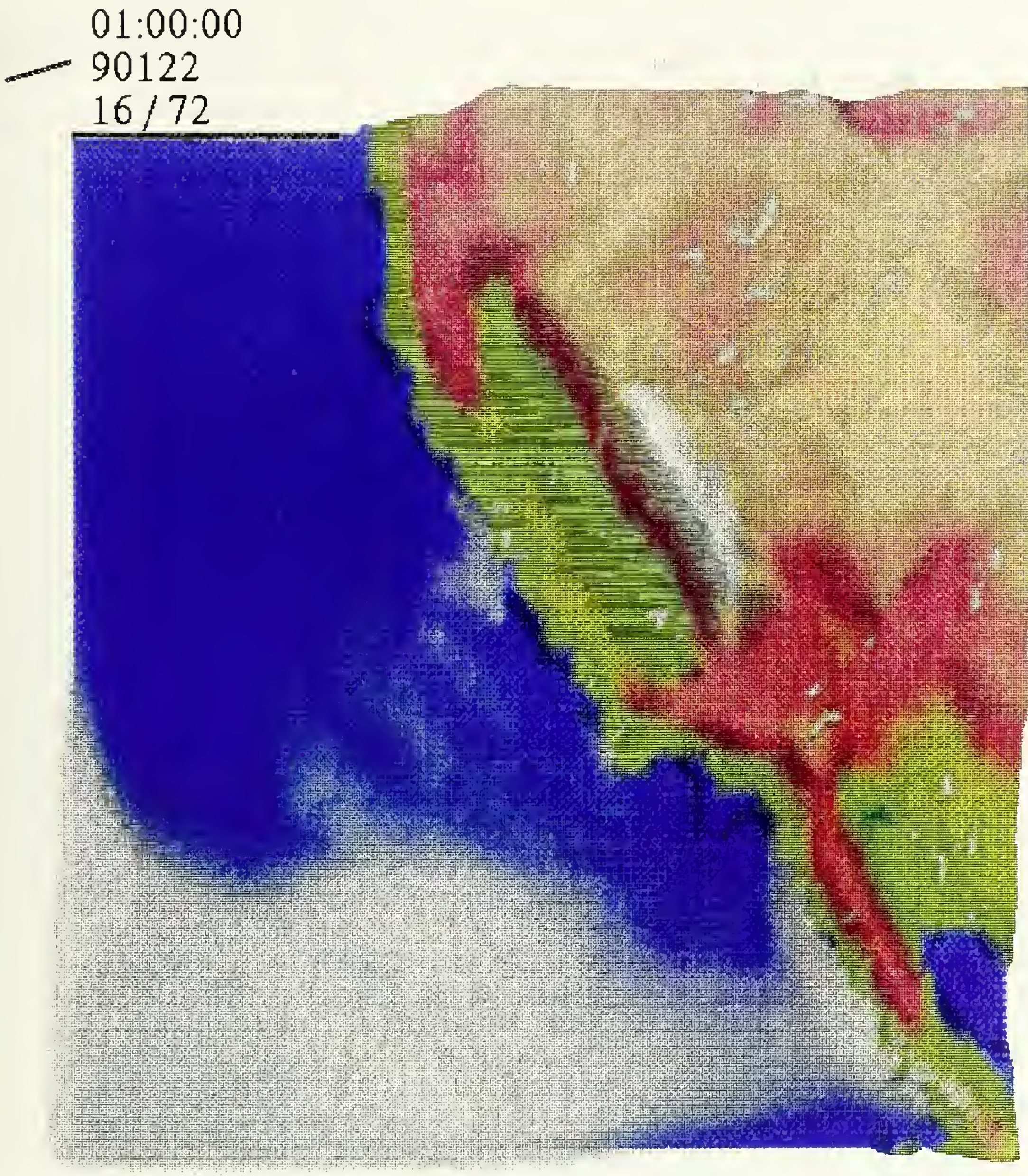

Figure 4. Model Stratus Cloud Fraction, 0800 UTC 02 May 90.

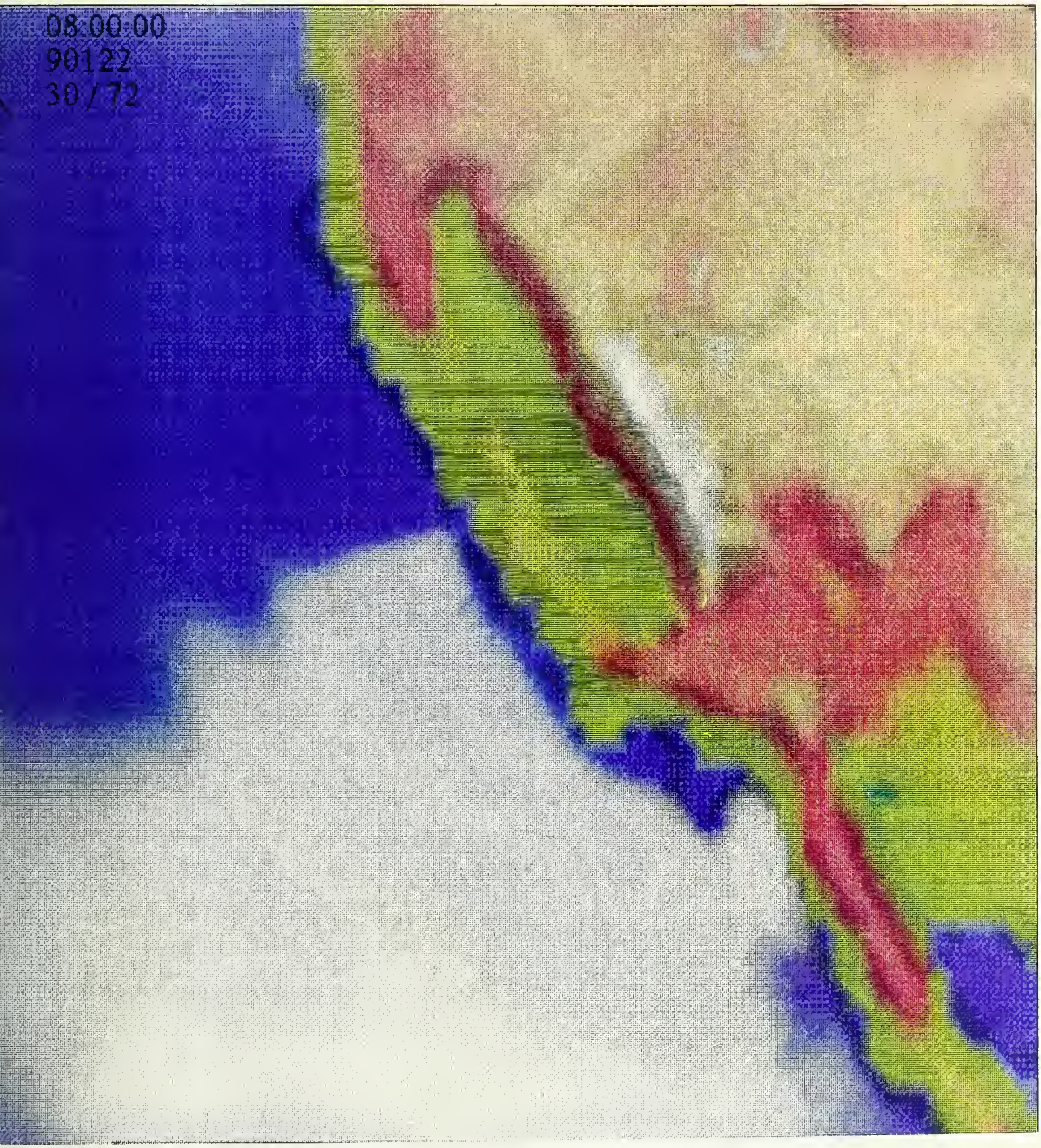

Figure 5. Model Stratus Cloud Fraction, 1500 UTC 02 May 90.

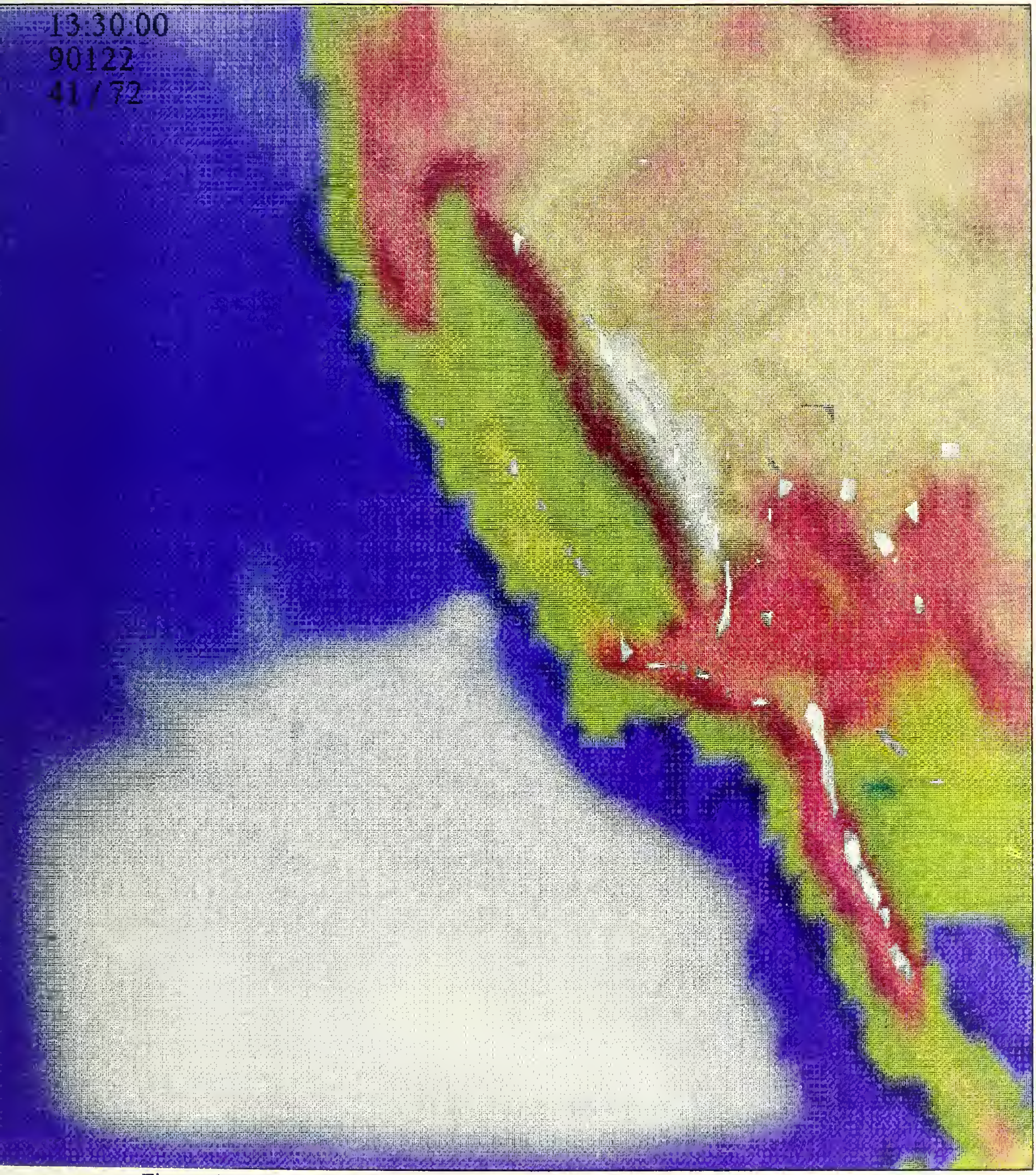

Figure 6. Model Stratus Cloud Fraction, 2030 UTC 02 May 90 (Convective Cloud Fraction Seen Over High Terrian).

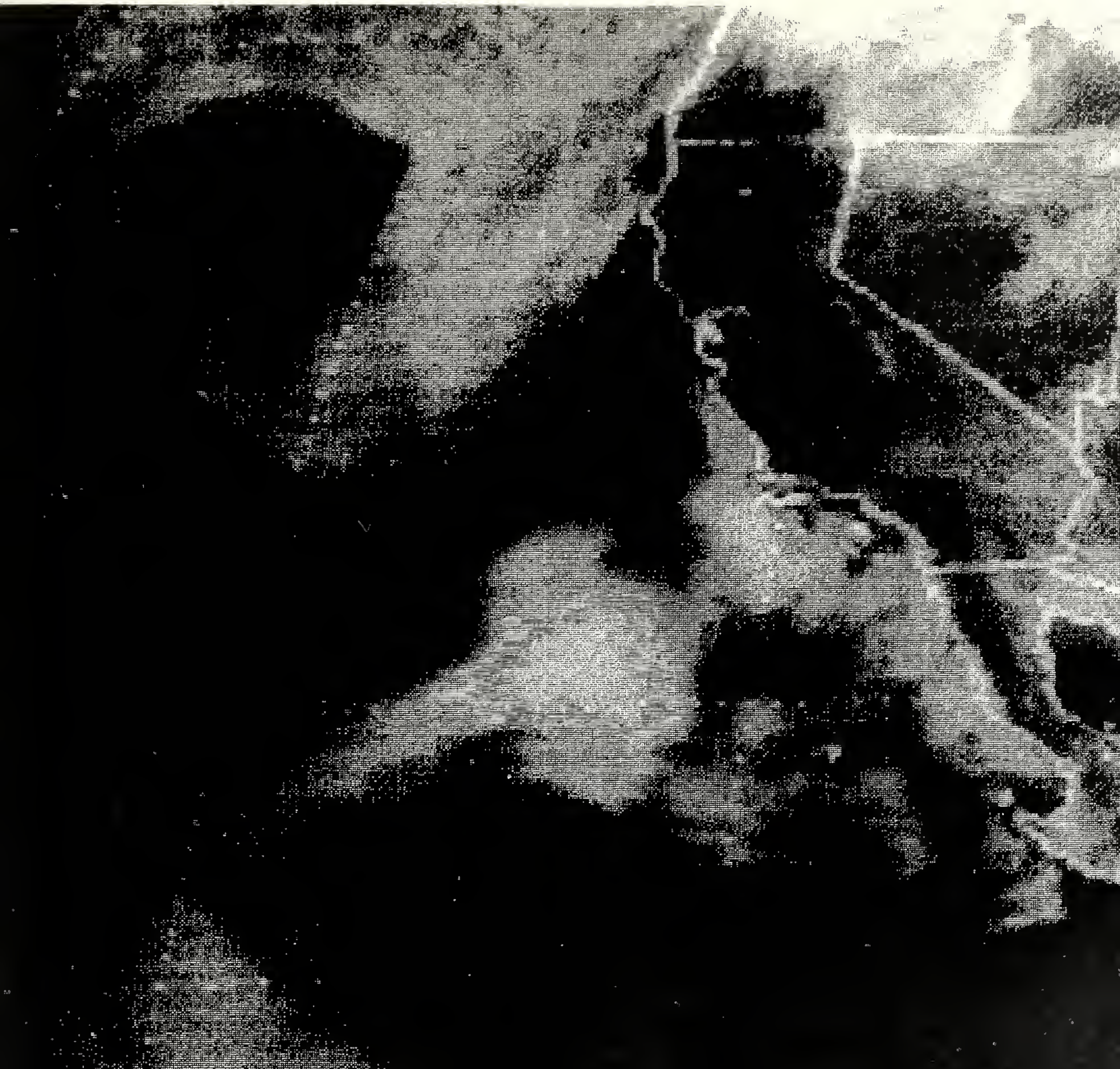

Figure 7. GOES Visible Satellite Image, 1501 UTC 02 May 90.

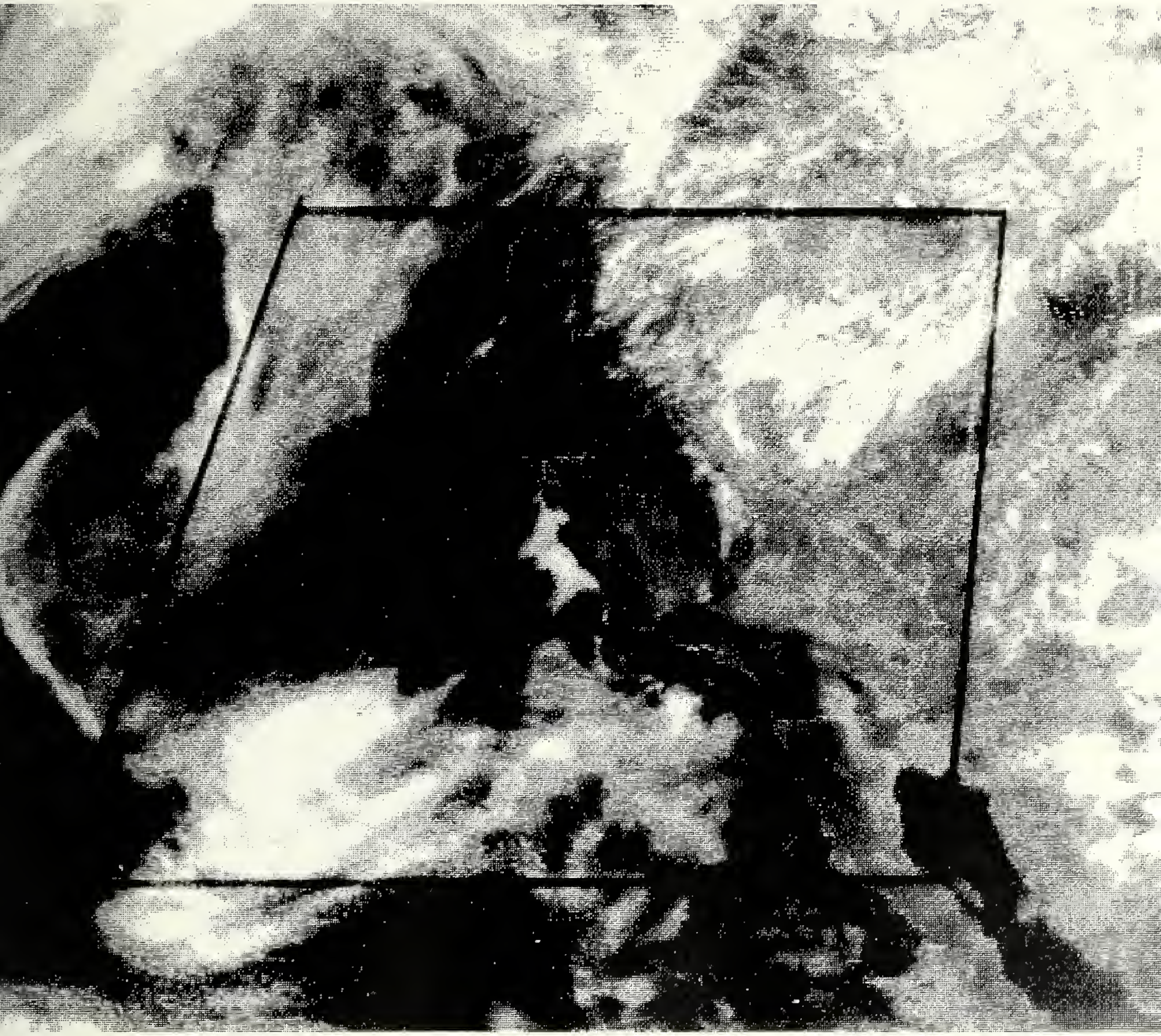

Figure 8. GOES Visible Satellite Image, 2031 UTC 02 May 90.

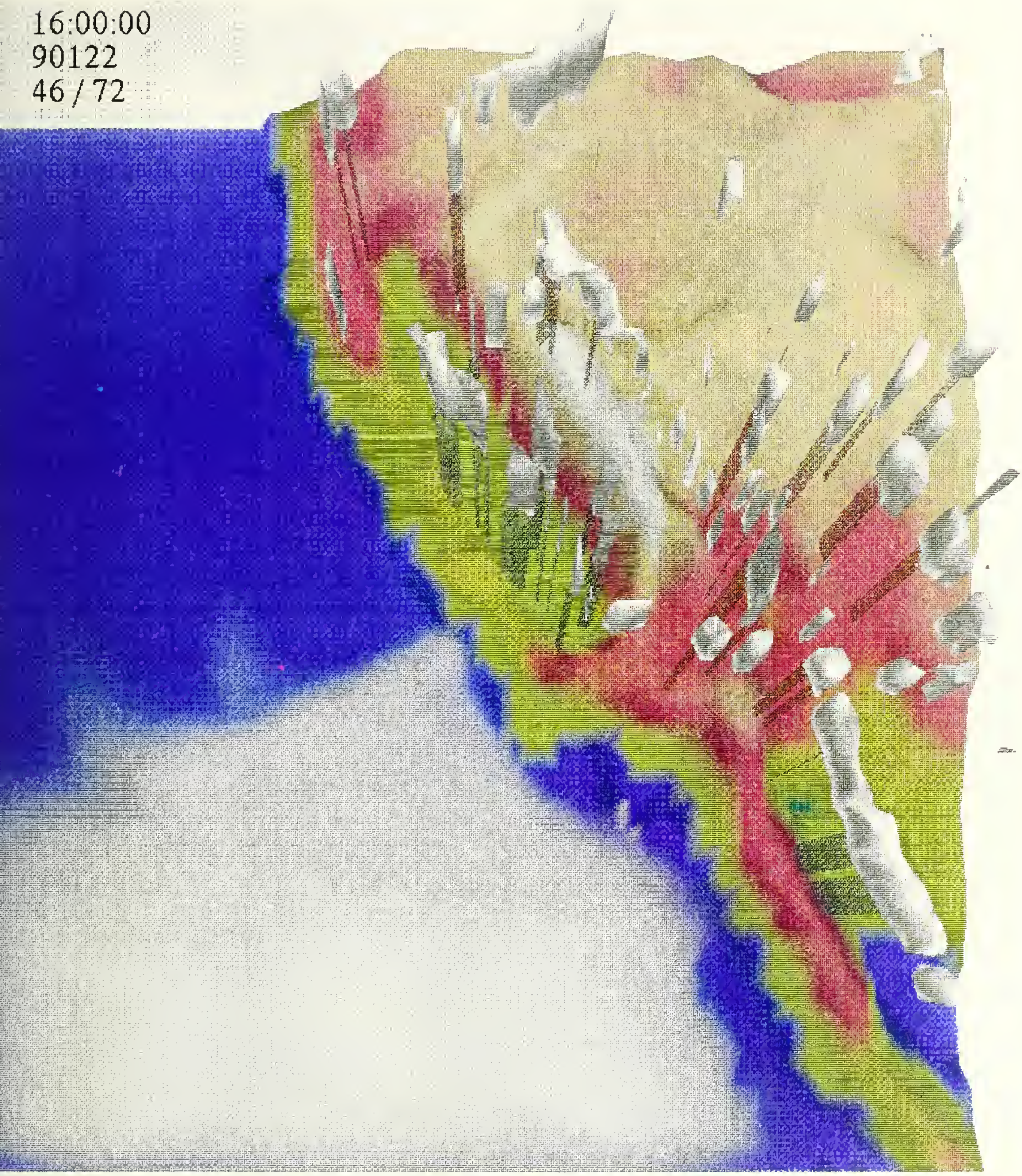

Figure 9. Model Convective Cloud Fraction with Convective Precipitation (gray shading under cloud), 2300 UTC 02 May 90.

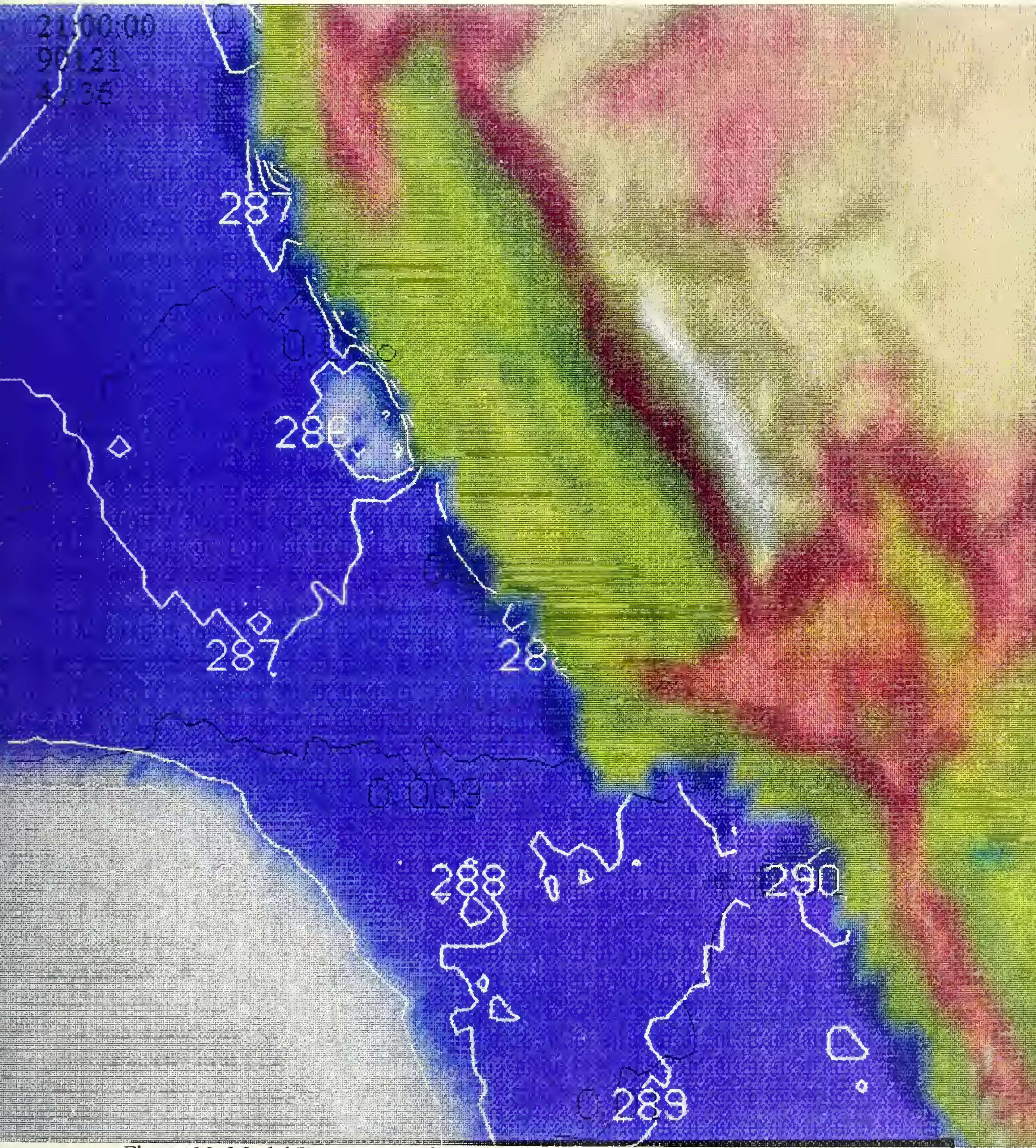

Figure 10. Model Temperature (K) as White Contours and Specific Humidity (g/g) as Black Contours at 50 m height, 0400 UTC 02 May 90.

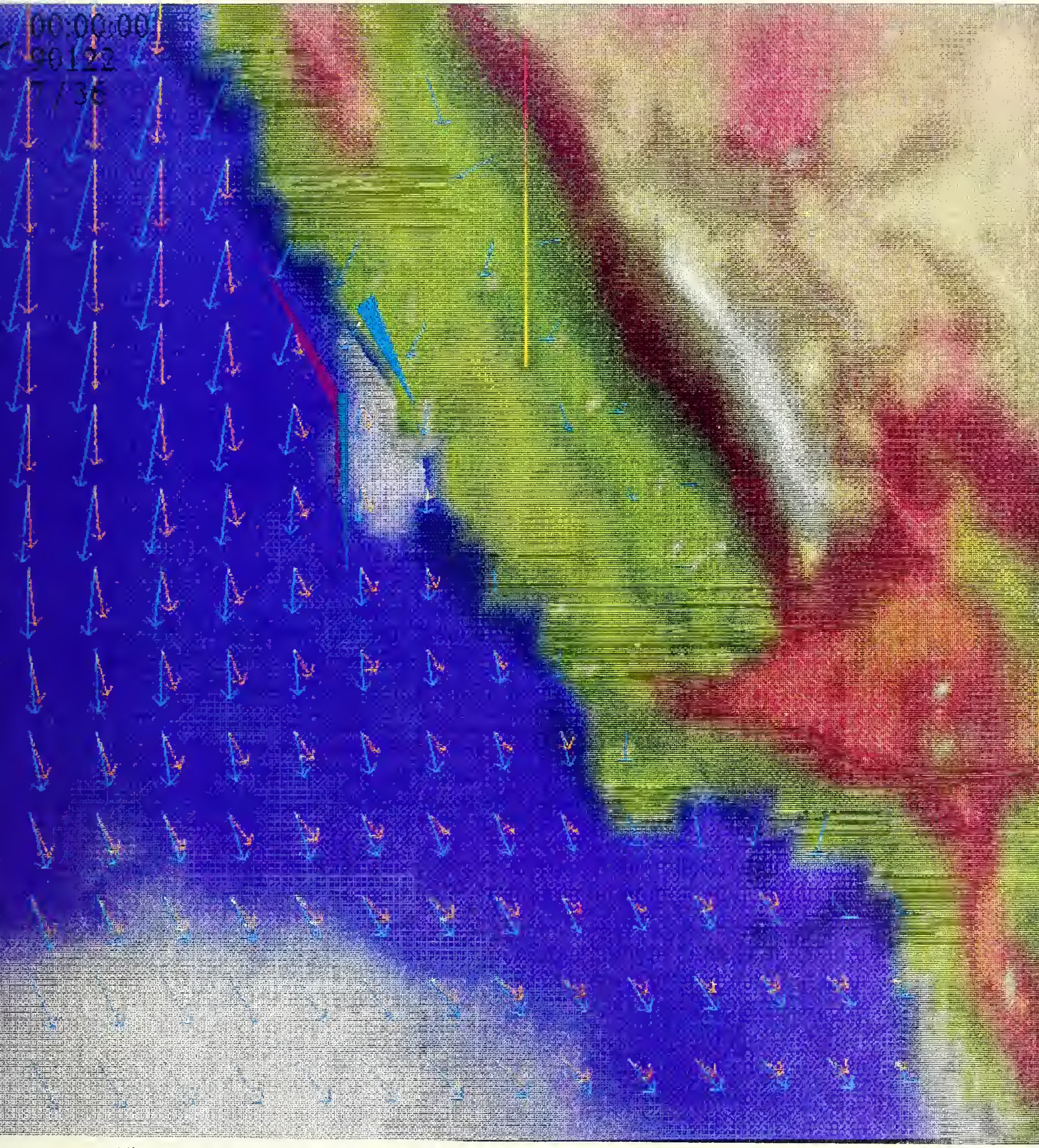

Figure 11. Model Wind Vectors - Purple vectors at 50 m height and Blue vectors at 250 m height, 0700 UTC 02 May 90.

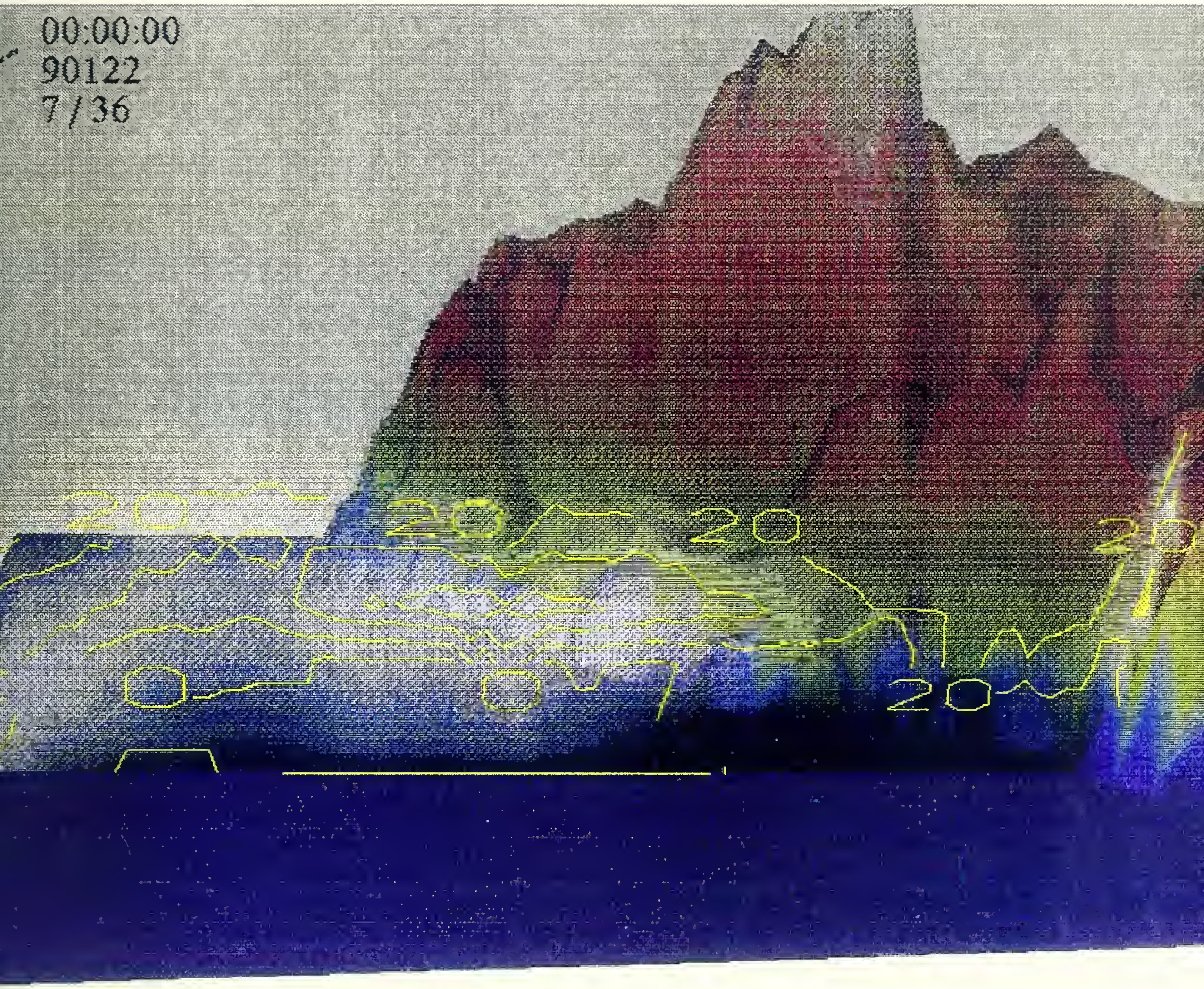

Figure 12. Cross-section of Model Longwave Cooling in the Free Atmosphere (contours) and Stratus (color slice) in degrees/day, 0700 UTC 02 May 90.

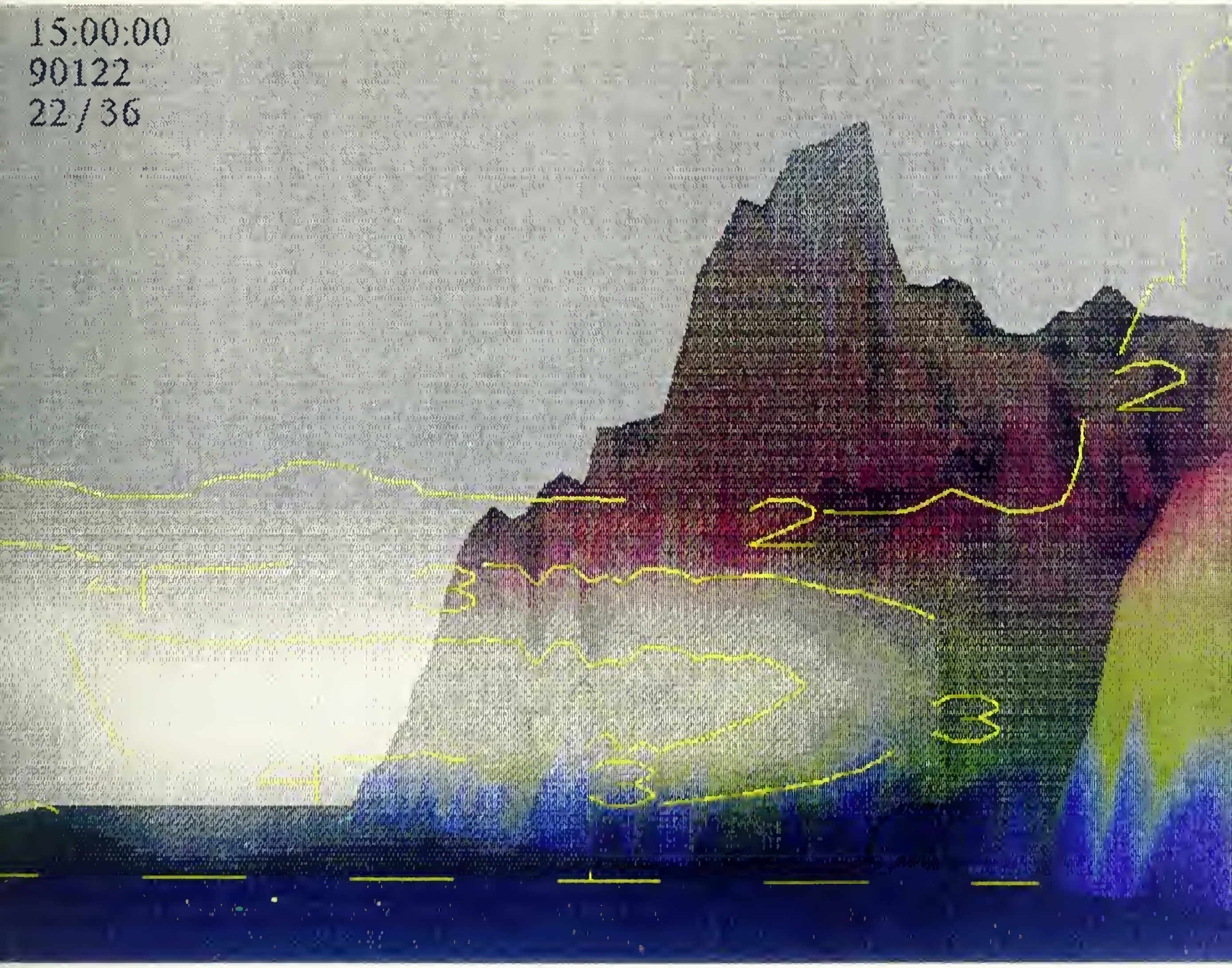

Figure 13. Cross-section of Model Shortwave Warming in the Free Atmosphere (contours) and Stratus (color slice) in degrees/day, 2200 UTC 02 May 90.

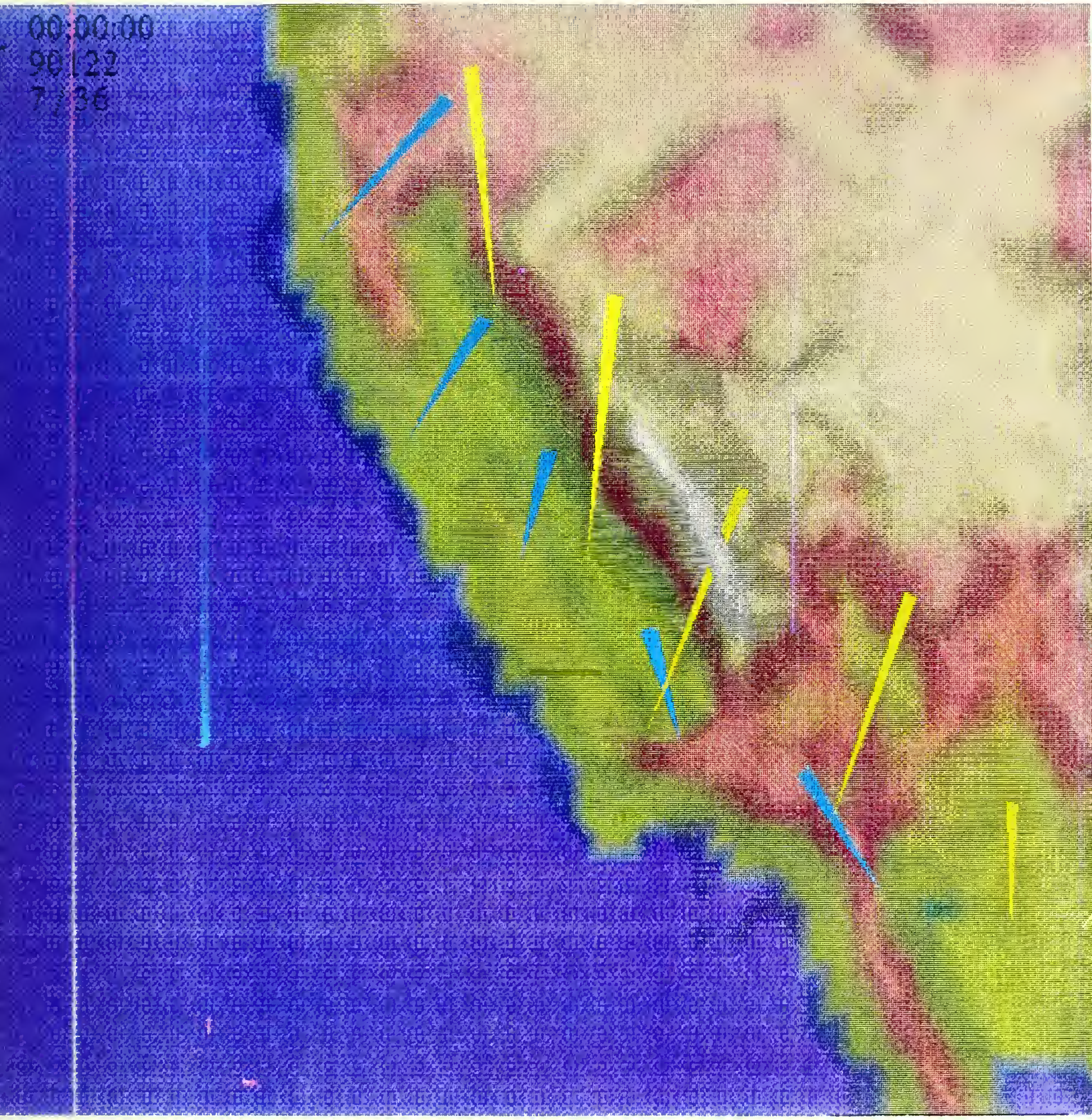

Figure 14. Model Upper Level Synoptic Wind Flow, Yellow Trajectories are at 500 mb (approximately 5500 m) and the Light Blue Trajectories are at 850 mb (approximately 2500 m), 0100 UTC 02 May 90.

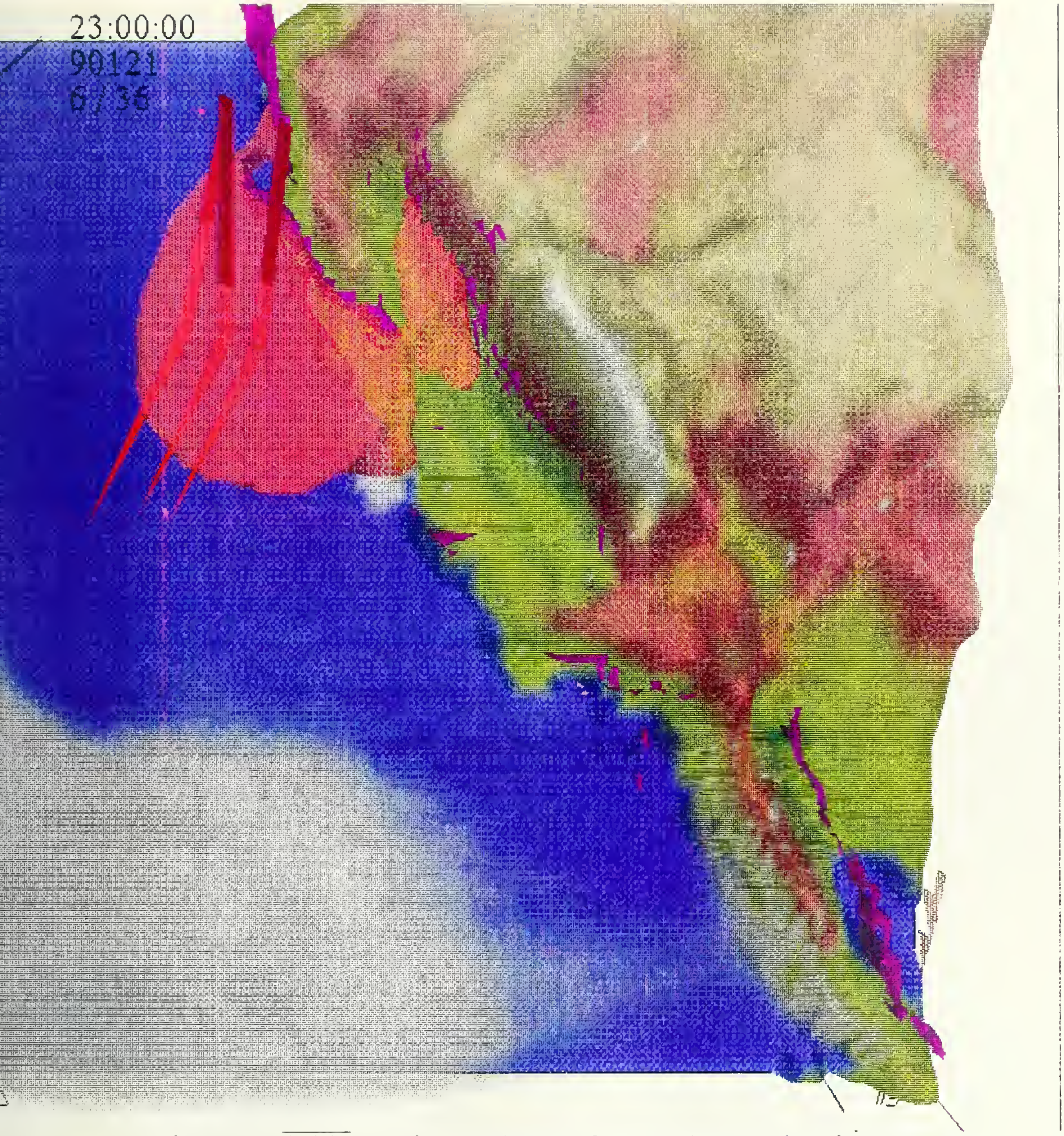

Figure 15. Model Dynamics, Purple Isosurfaces are downward motion greater than 30 cm/sec, Red Arrows are Air Parcel Trajectories, and Red Isosurfaces are temperatures greater than 292 K, 0600 UTC 02 May 90.

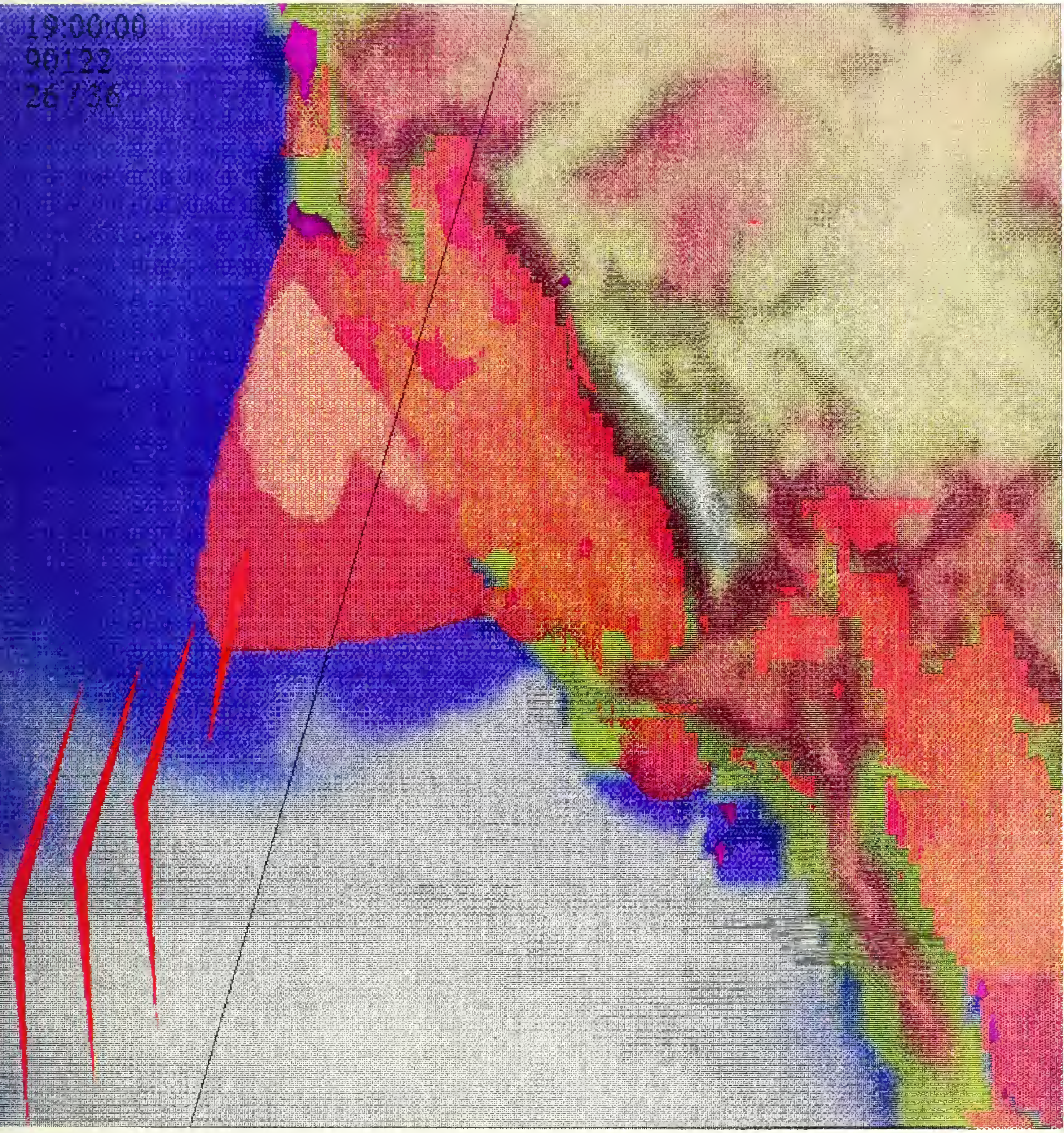

Figure 16. Model Dynamics, Purple Isosurfaces are downward motion greater than 30 cm/sec, Red Arrows are Air Parcel Trajectories, Red Isosurfaces are temperatures greater than 292 K, and Wind Isotach of Coastal Jet (Green Isosurface at 25 m/s), 0200 UTC 03 May 90.

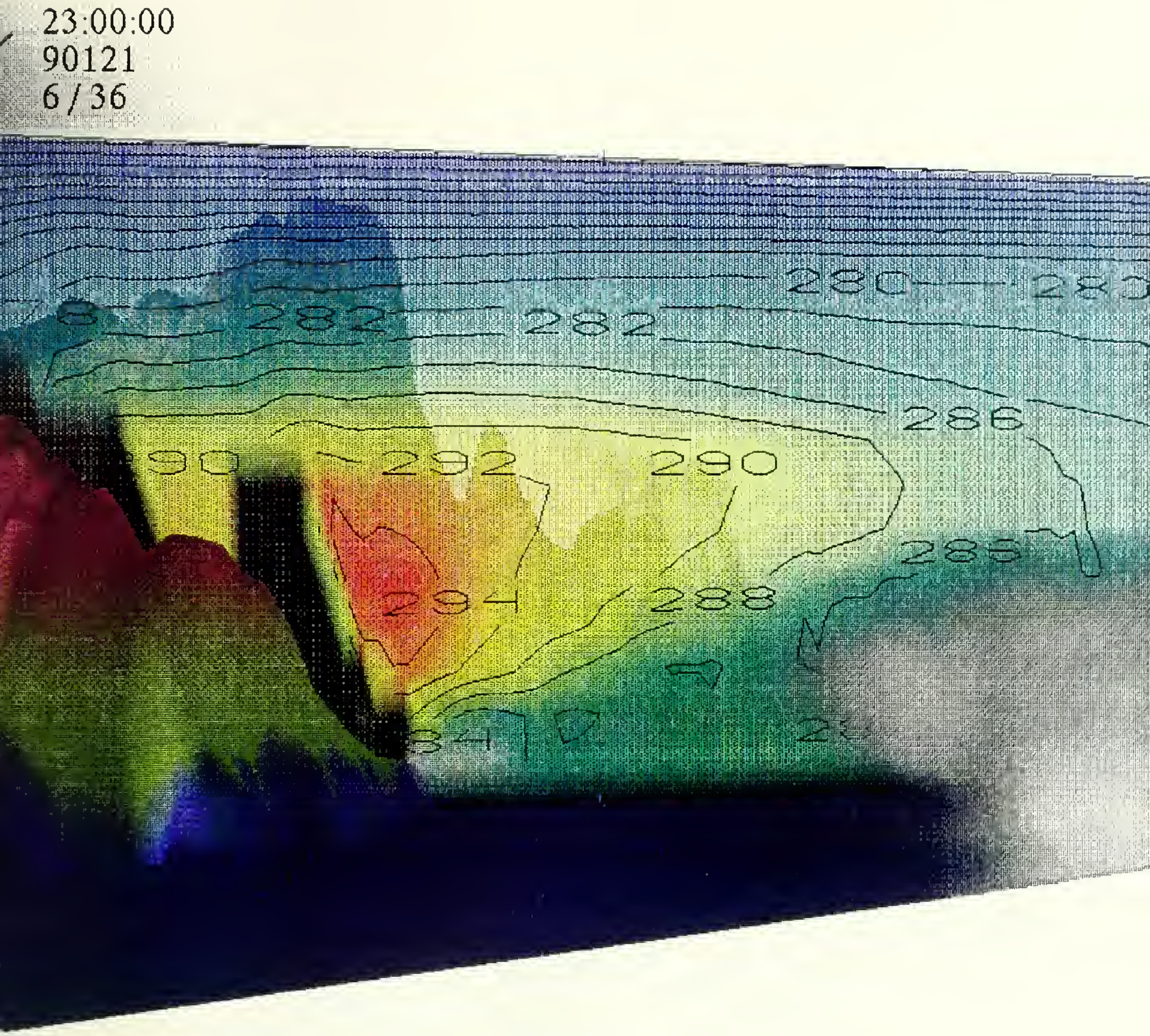

Figure 17. Cross Sectional View of Model Temperature (K), 0600 UTC 02 May 90.

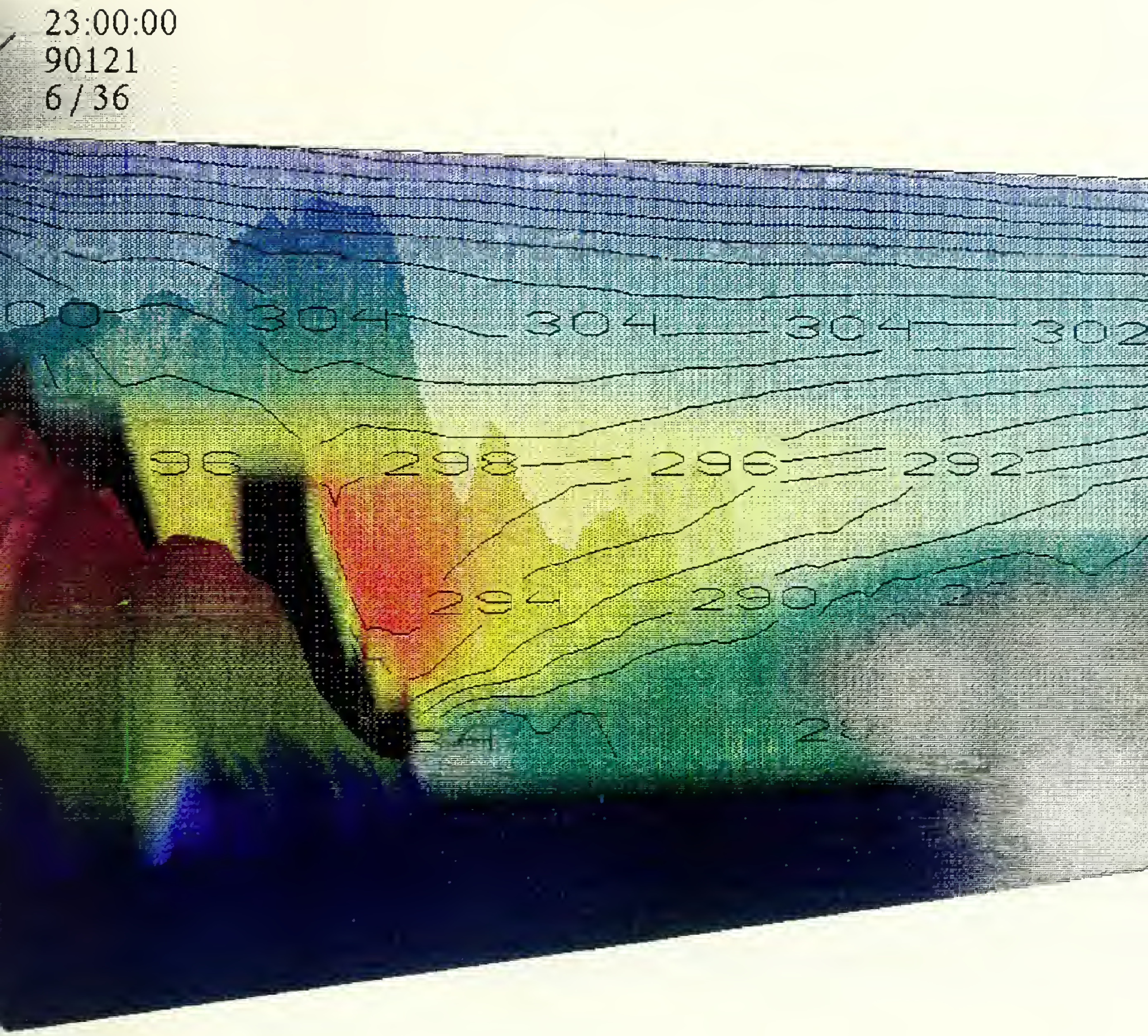

Figure 18. Cross Sectional View of Potential Temperature (K), 0600 UTC 02 May 90.

19:00:00
90122
26 / 36

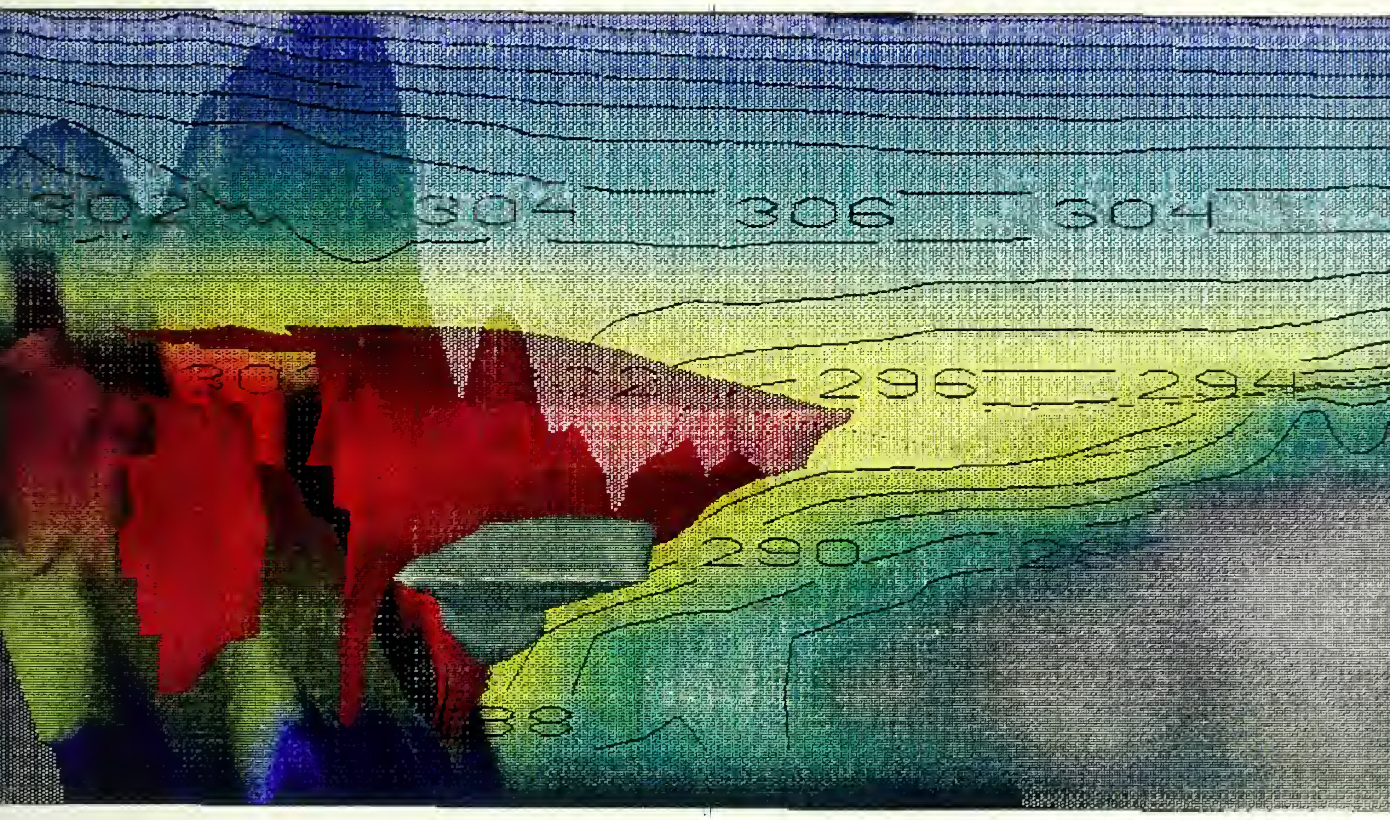

Figure 19. Cross Sectional View of Potential Temperature Contours (K), Red 292 K Temperature Isosurface and Wind Isotach of Coastal Jet (Green Isosurface at 25 m/s located under Red Temperature Isosurface), 0200 UTC 03 May 90.

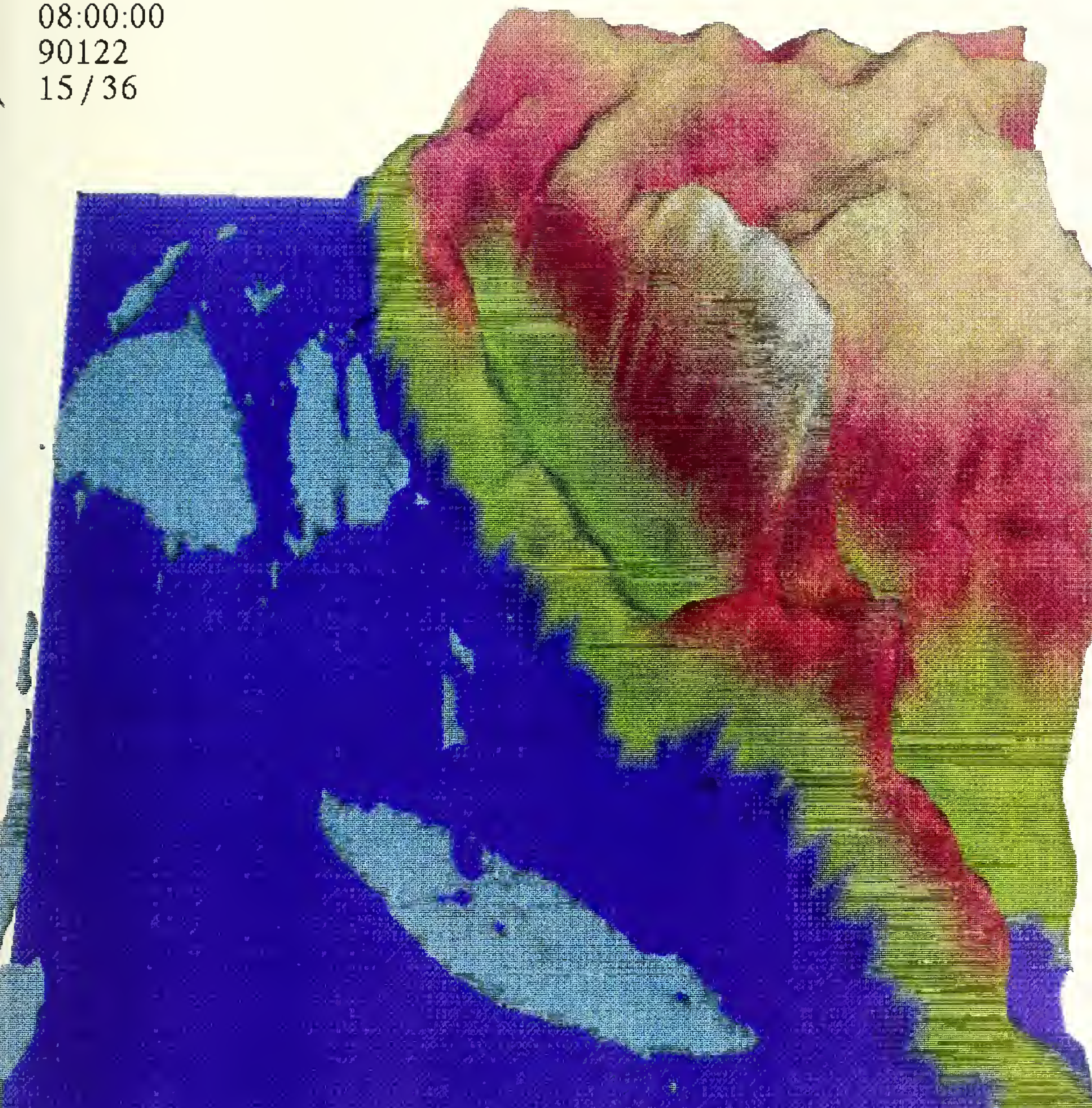

Figure 20. Atmospheric Trapping of Radar Propagation (negative dM/dz),
1500 UTC 02 May 90.

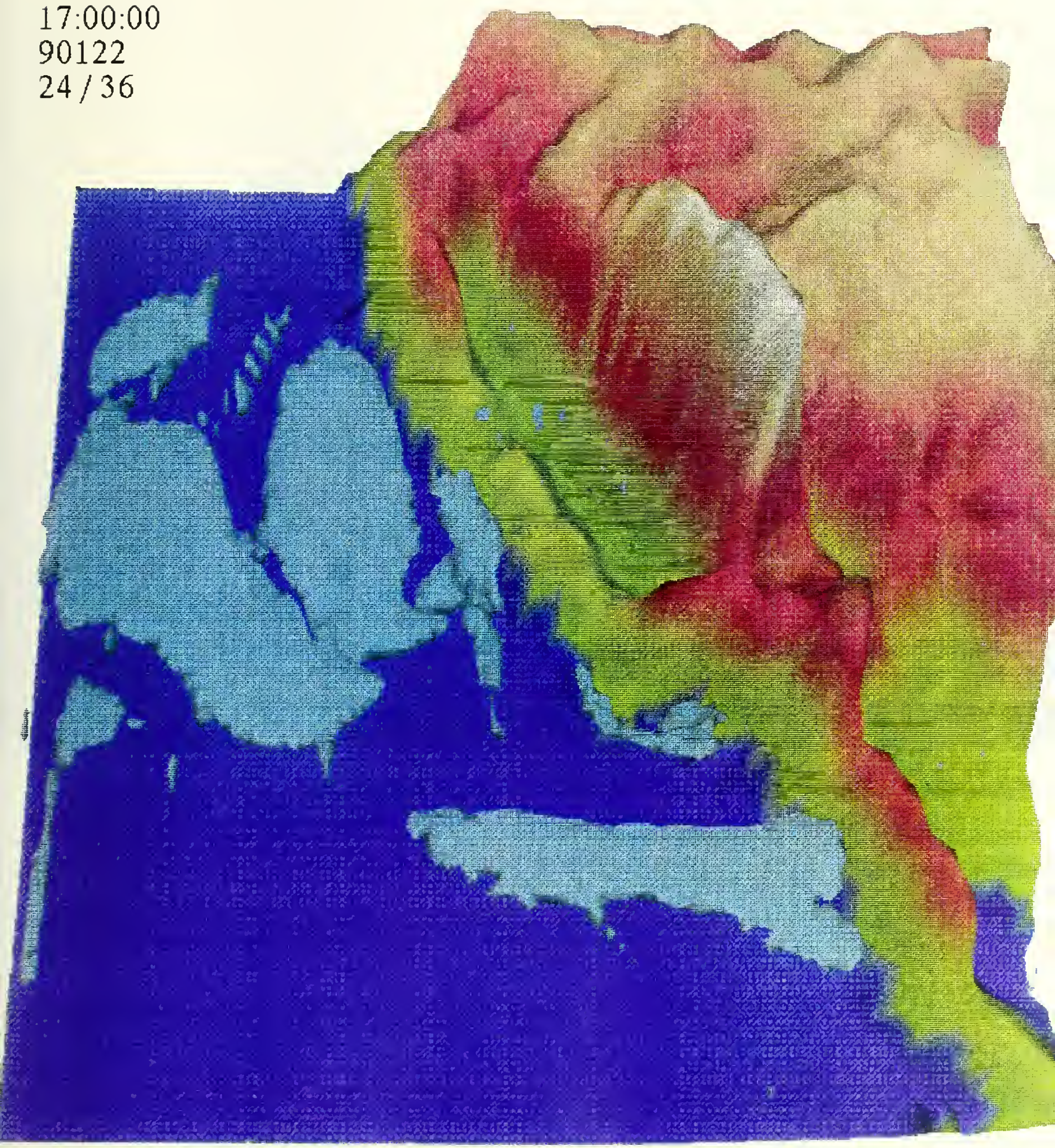

Figure 21. Atmospheric Trapping of Radar Propagation (negative dM/dz),
0000 UTC 03 May 90.

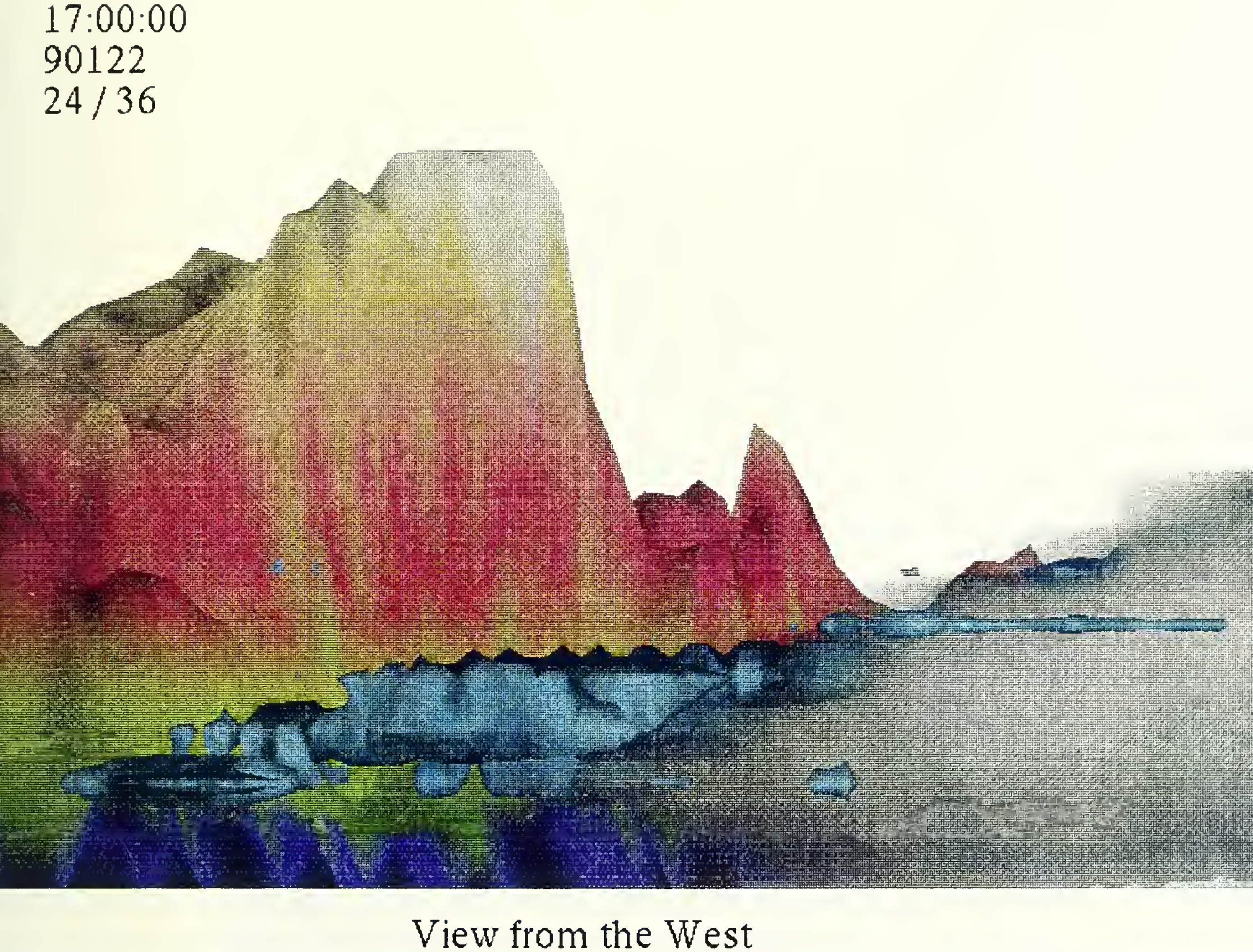

Figure 22. Side View of Atmospheric Trapping of Radar Propagation (negative dM/dz), 0000 UTC 03 May 90.

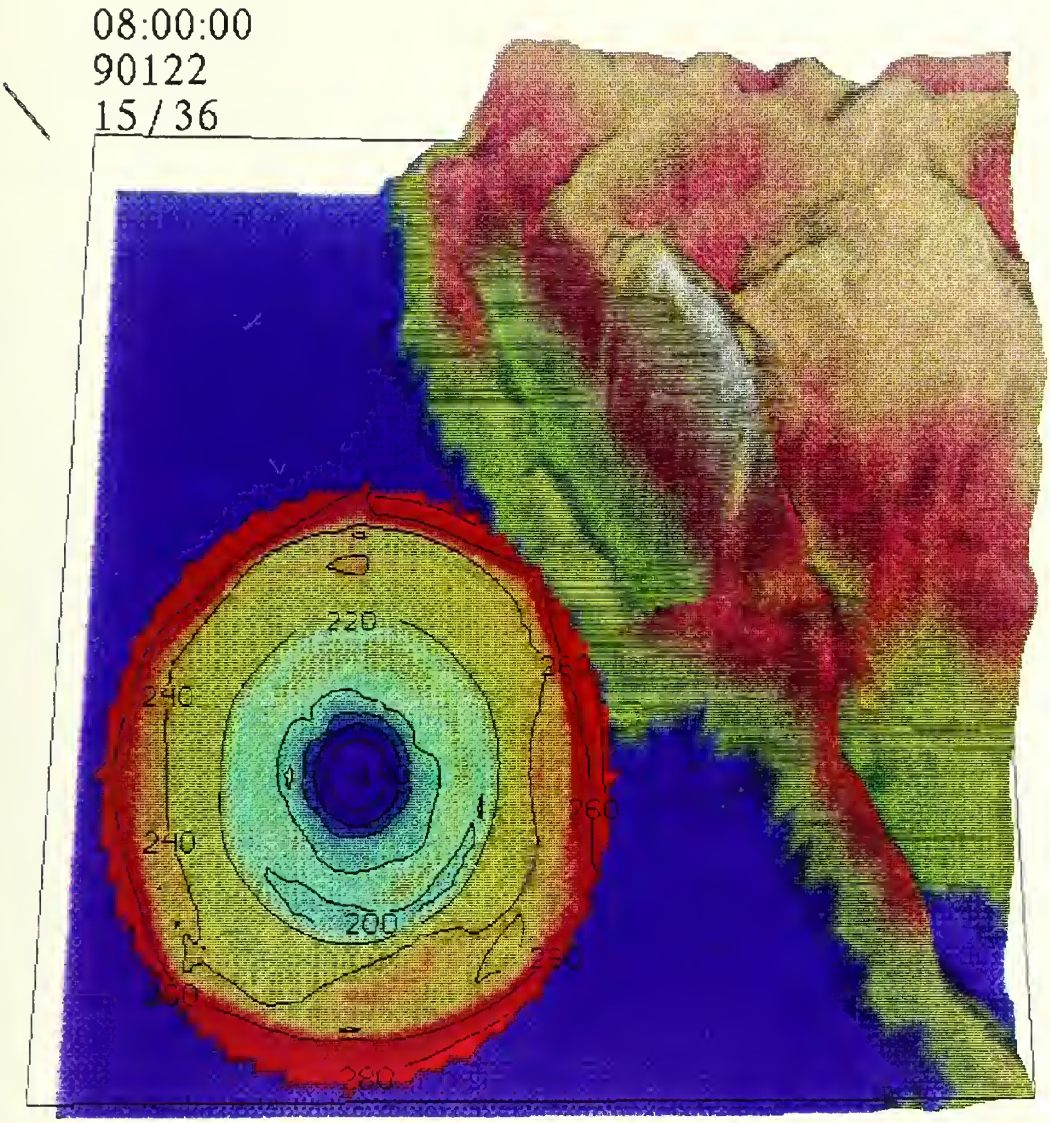

Figure 23. RPO Radar Propagation at 300 m Height, 1500 UTC 02 May 90.

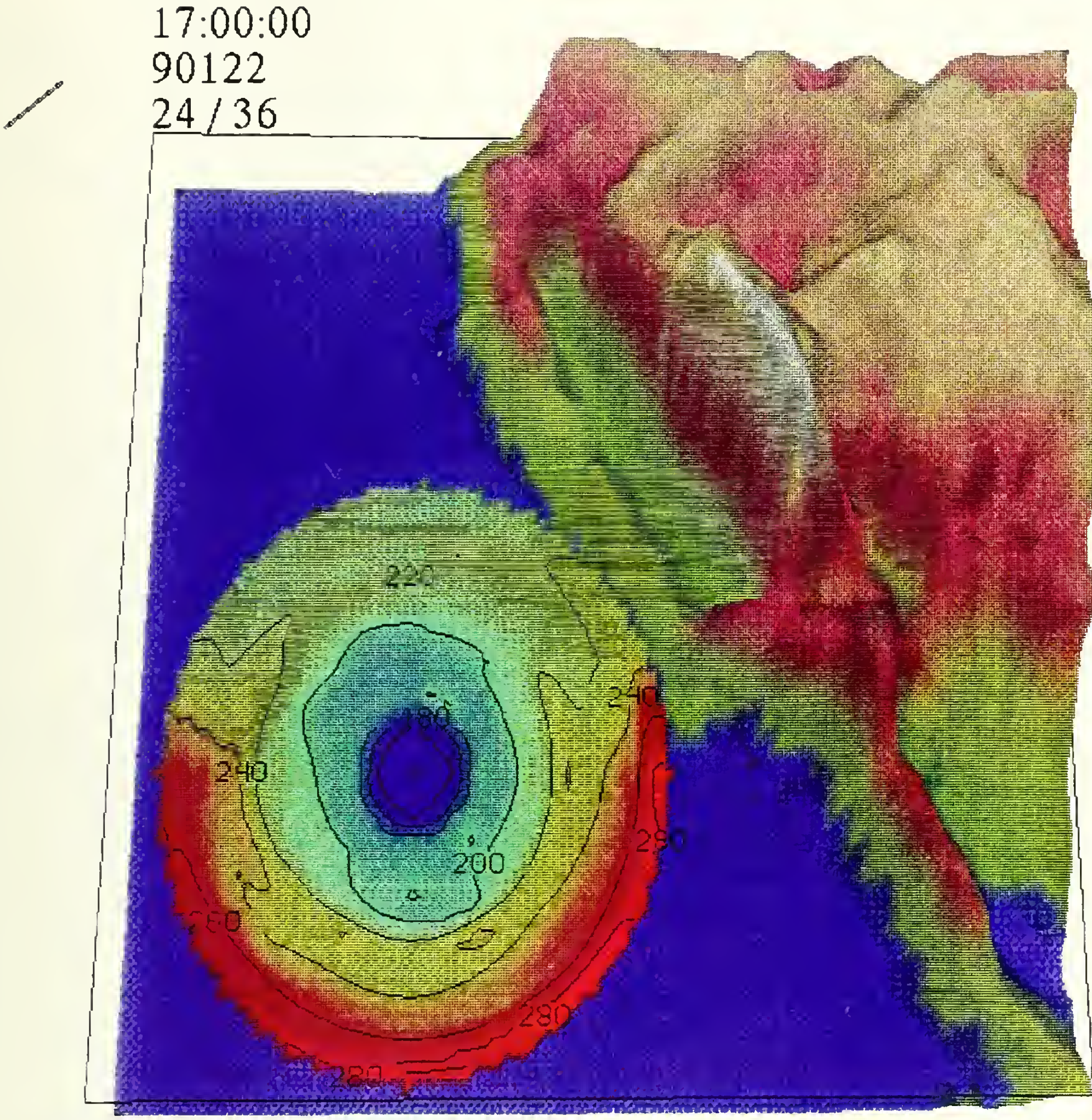

Figure 24. RPO Radar Propagation at 300 m Height, 0000 UTC 03 May 90.

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